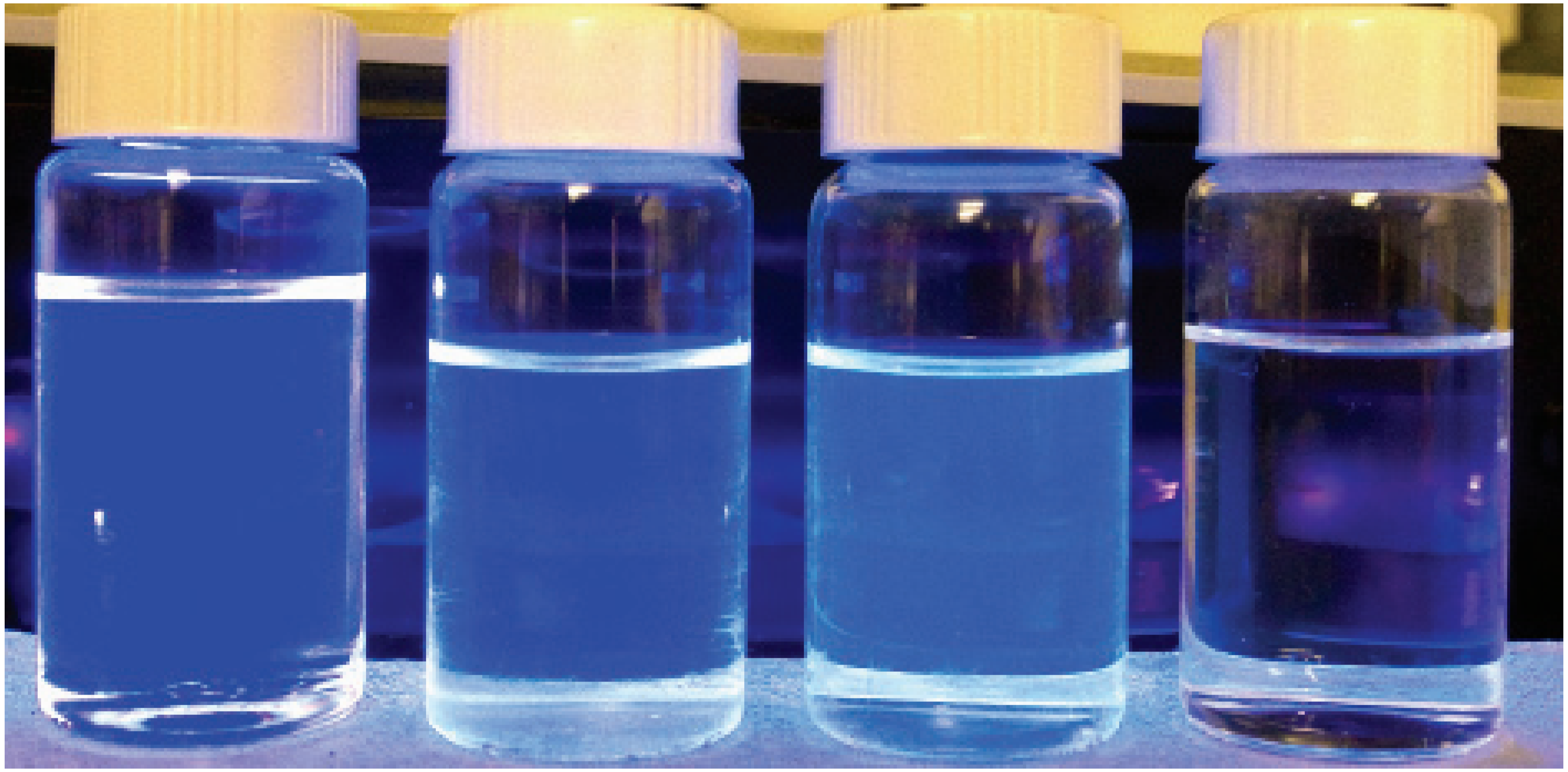
Water-based liquid scintillator: A new detection medium



David E. Jaffe*, BNL, 20151006

*Cohort: **L.J.Bignell**, M.V.Diwan, S.Hans, *L.Capelluto*, S.Kettell, R.Rosero, B.Viren, E.Worcester, M.Yeh, C.Zhang [D.Beznosko, H.Themann]

BROOKHAVEN NATIONAL LABORATORY

Supported by DOE KA2501032, BNL LDRD 12-03 and Technology Maturation Award 14-002

U.S. DEPARTMENT OF ENERGY | Office of Science

What I'm going to talk about

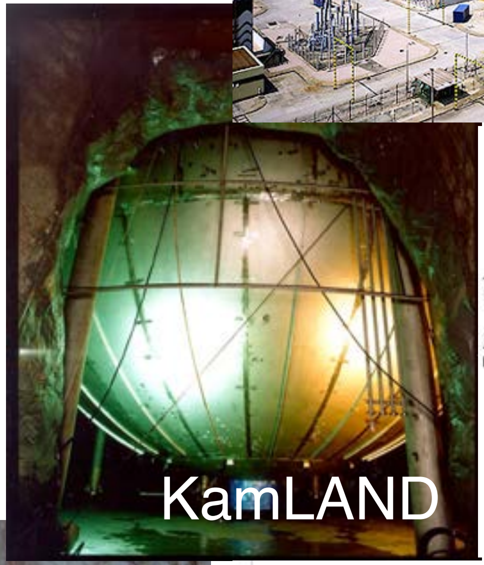
1. Why Water-based Liquid Scintillator (WbLS)?
    1. Successful applications of liquid scintillator(LS) and water Cerenkov detectors
    2. Possible applications of WbLS
2. WbLS properties of interest
3. Measurements
    1. Results
    2. In-progress
4. Summary and prospects

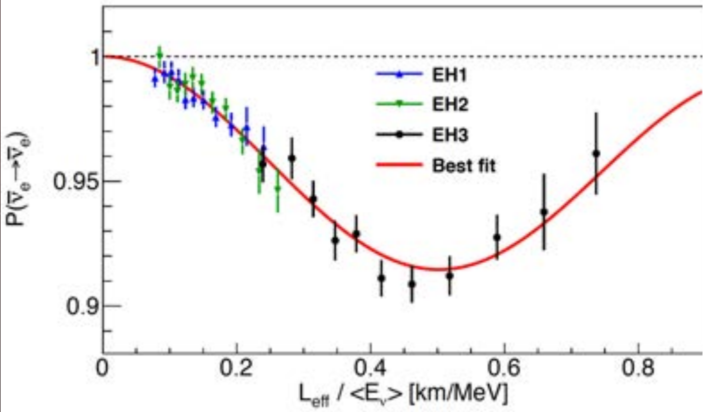
Reactor Neutrinos - A Tool for Discoveries

A flavor pure source of $\overline{\nu}_e$

2012 - Measurement of θ_{13} with Reactor Neutrinos

2008 - Precision measurement of Δm_{12}^2 . Evidence for oscillation

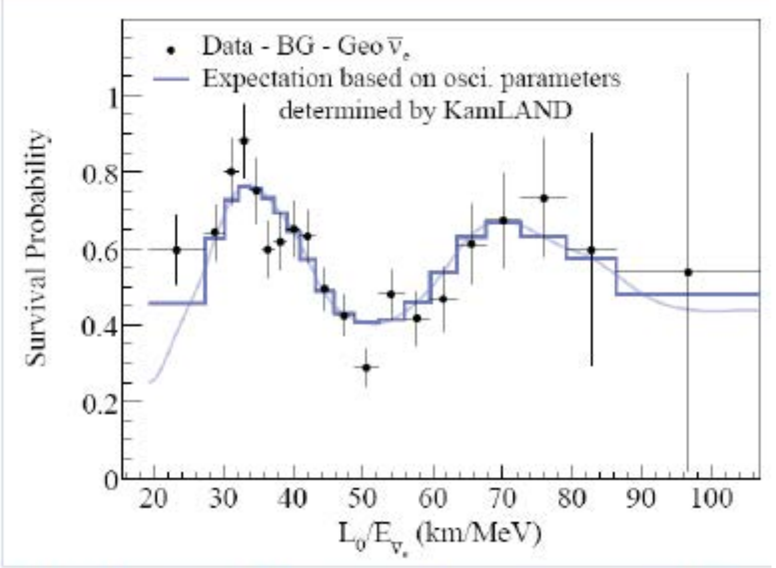




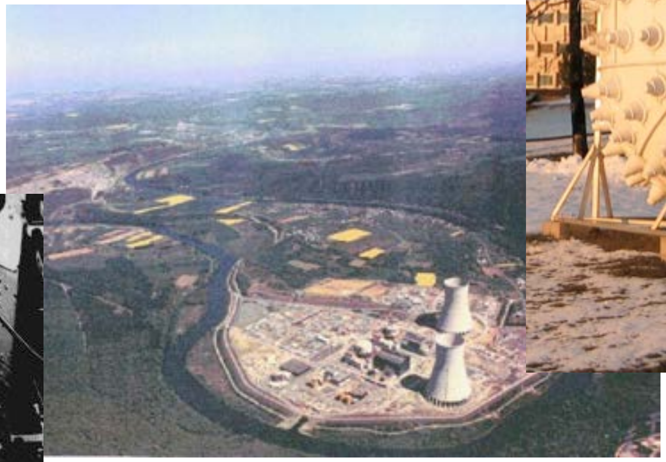
2003 - First observation of reactor antineutrino disappearance

1995 - Nobel Prize to Fred Reines at UC Irvine

1980s & 1990s - Reactor neutrino flux measurements in U.S. and Europe



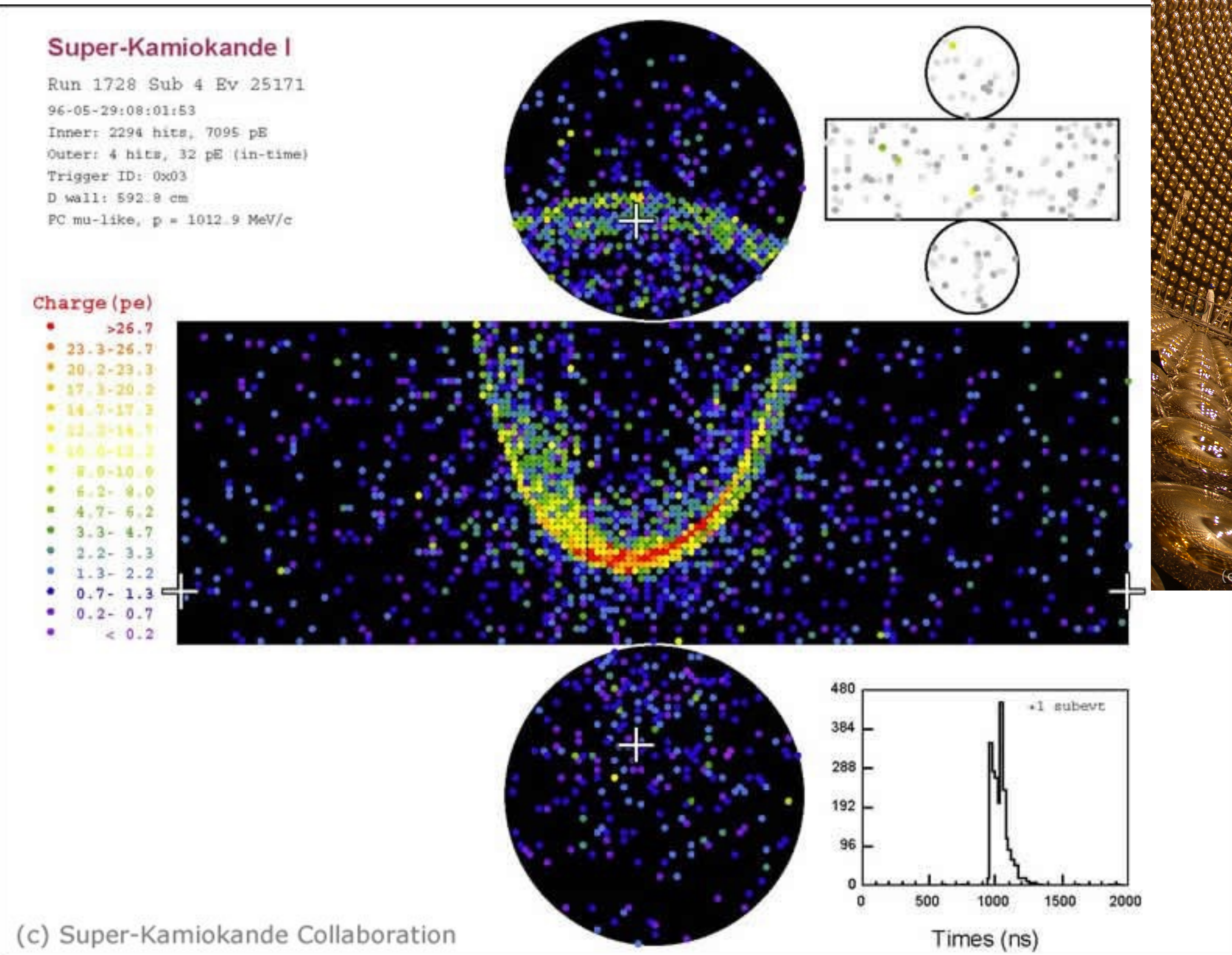
1956 - First observation of (anti)neutrinos

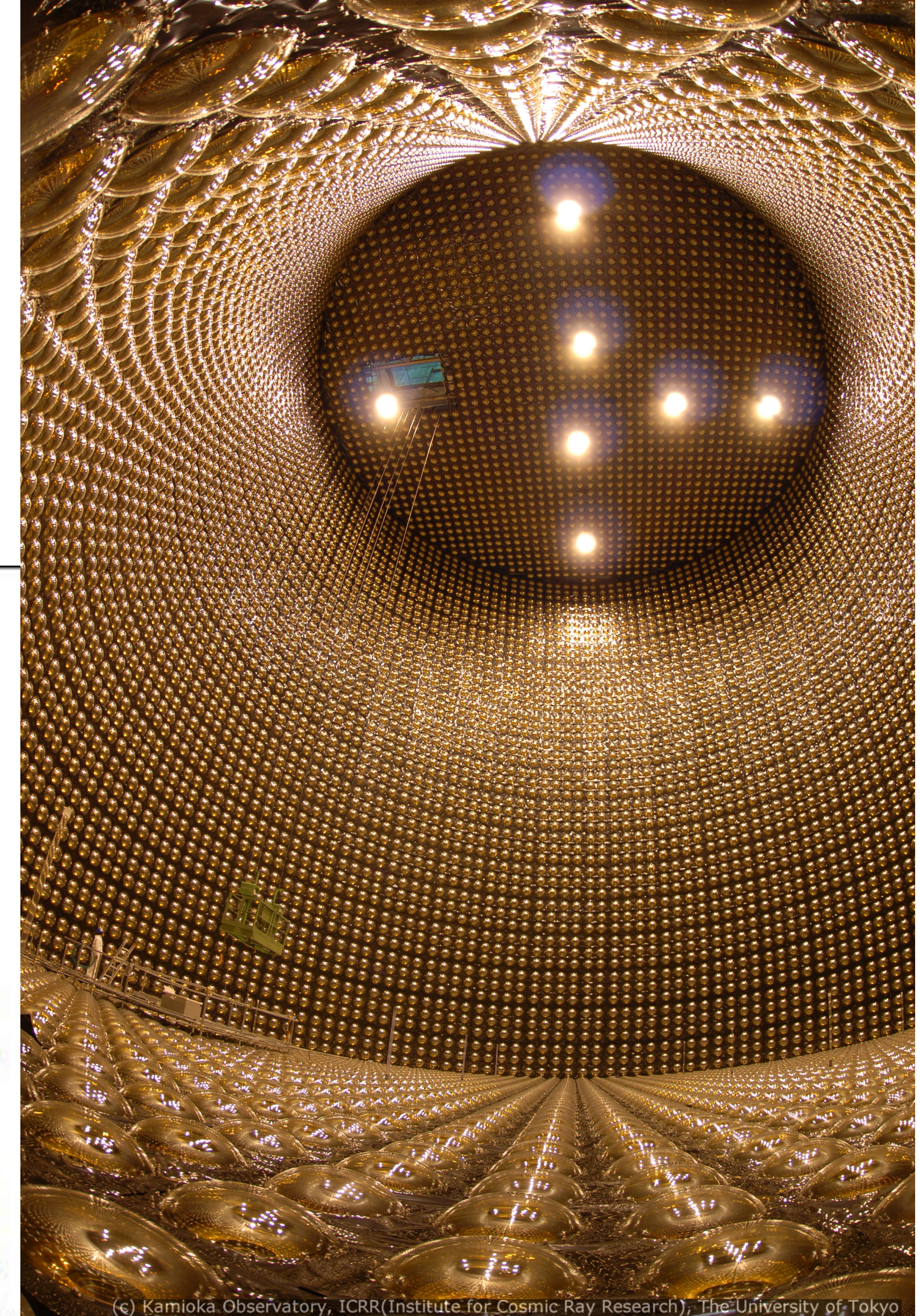


>55 years of liquid scintillator detectors
a story of varying baselines...

Super-Kamiokande

Stainless steel cylinder (diameter 39m, height 42m) filled with ~50kilotons of ultrapure water instrumented with ~11k 20” PMTs for ~40% photocathode coverage

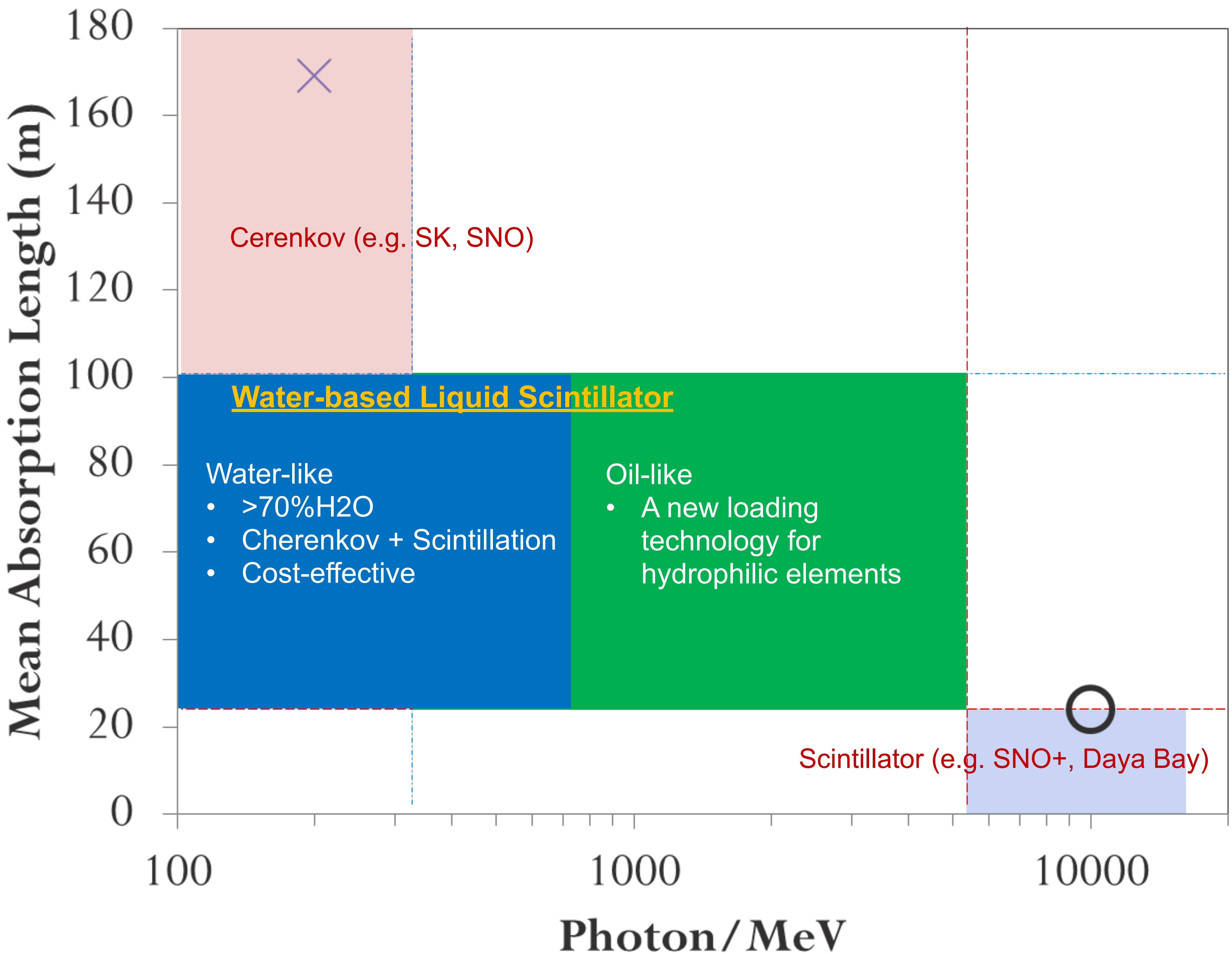




Nucl. Instrum. Methods Phys. Res., Sect. A **501**, 418 (2003).

http://www-sk.icrr.u-tokyo.ac.jp/sk

WbLS conceptually: Absorption length vs light yield



WbLS properties

WbLS is an emulsion and was developed by Minfang Yeh of the Neutrino and Nuclear Chemistry Group in the BNL Chemistry Department

1. Adjustable scintillation light yield (~0.5 to ~15% LS added to water)

2. Long attenuation length (LS~20m, water ~100m)

3. Particle identification/reconstruction:

    1. Directional (Cerenkov) and isotropic (Scintillation) light

    2. Timing of prompt Cerenkov and scintillation light

    3. Energy measurement via calorimetry (scint.) and Cerenkov threshold

4. Low-cost: Primary material is pure water

5. Environmentally and chemically friendly

6. Enables dissolution of lipophobic but hydrophilic metals

Some applications

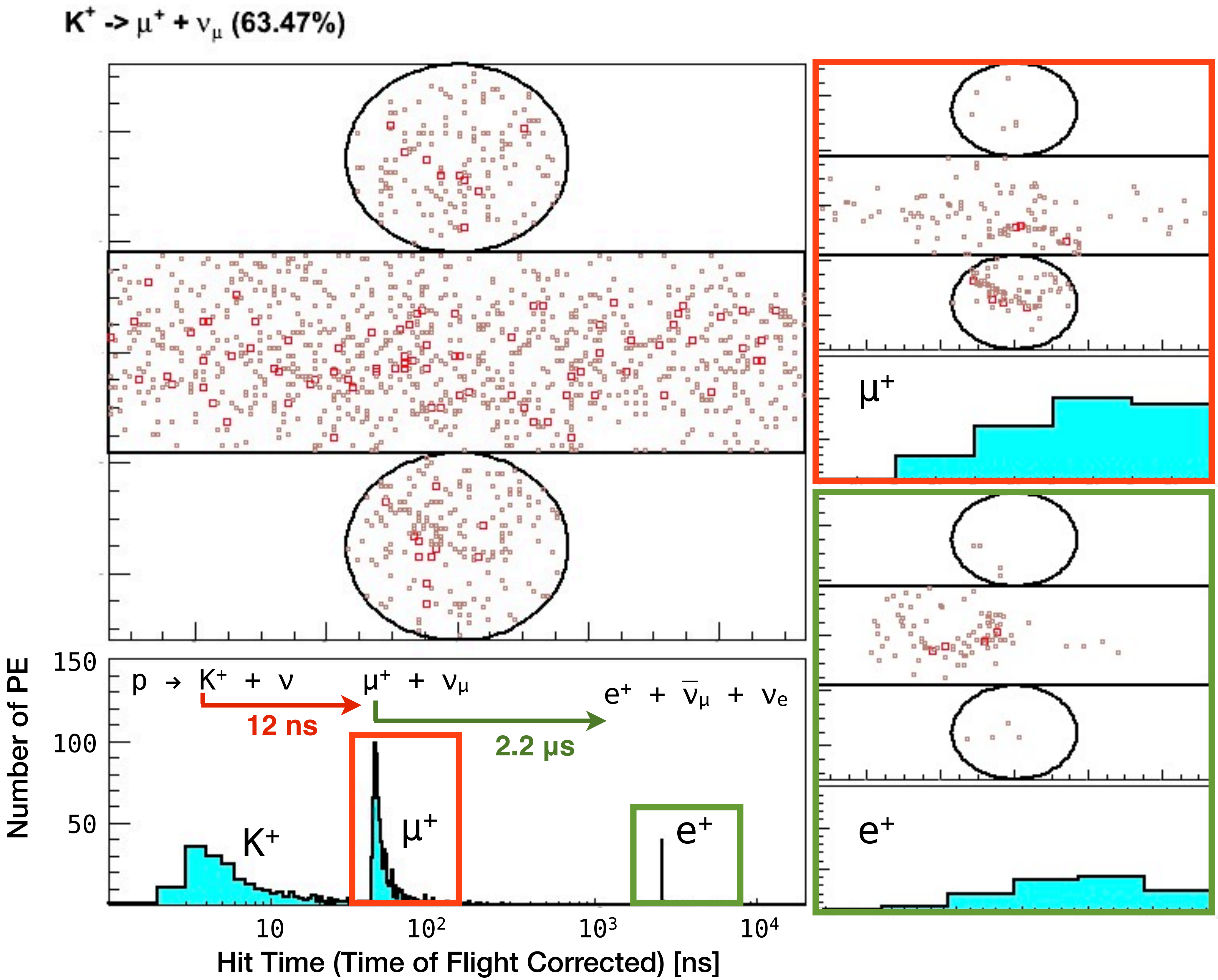
1. $p \rightarrow K^+ \nu$: Favored by a number SUSY GUTs, K^+ is below Cerenkov threshold in water, WbLS makes K^+ detectable

2. Neutrino-less double-beta decay ($0\nu\beta\beta$): Are neutrinos Dirac or Majorana particles? WbLS + improved photodetector may be a way to access isotopes at the ~50ton-scale

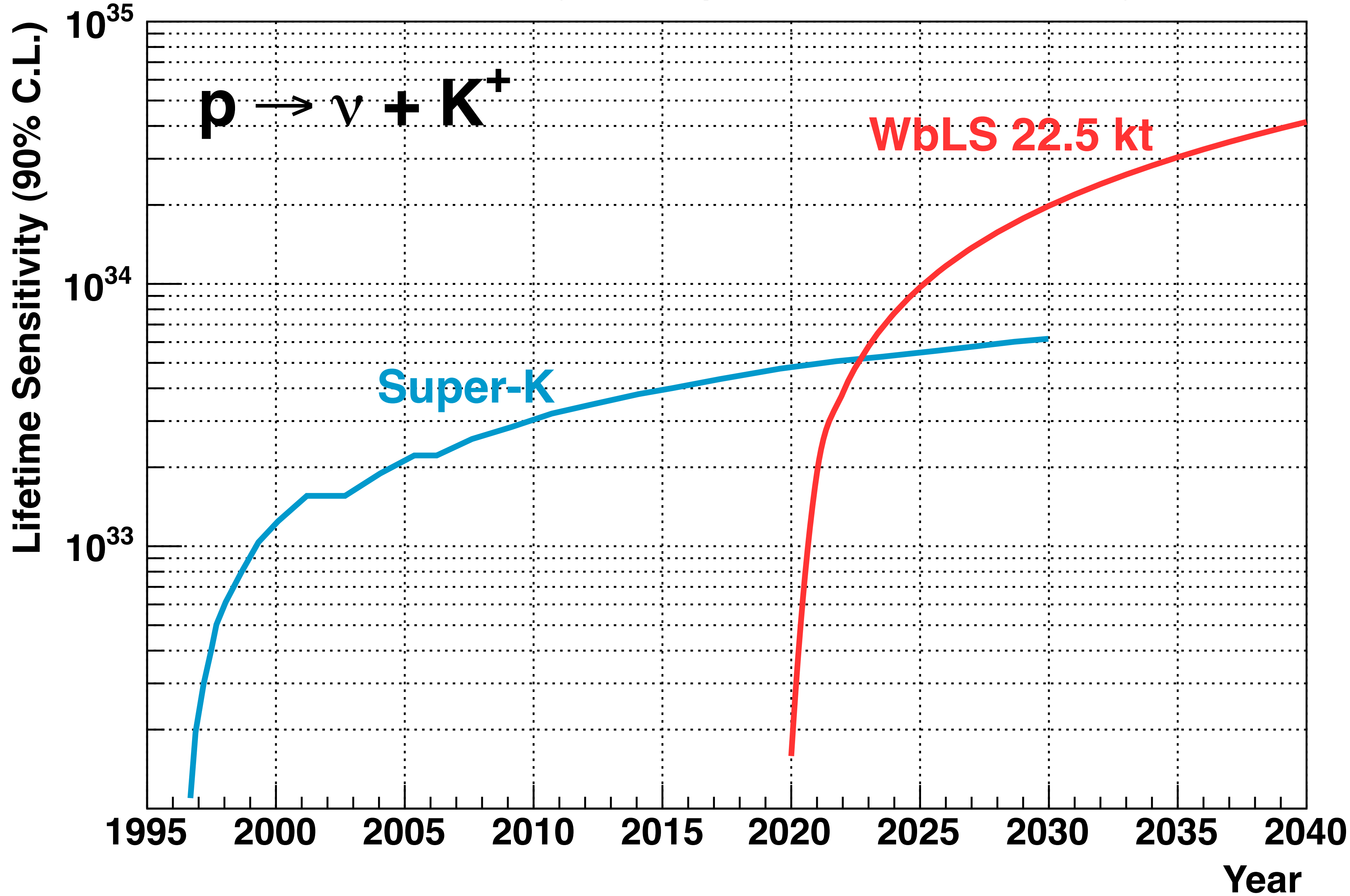
3. Beam therapy quality assurance: Real-time hadron therapy dose verification in water-equivalent phantom

Increased sensitivity to proton decay with WbLS

Simulated event with 90 optical photons/MeV (**~1% WbLS**) in a SuperKamiokande-sized detector. Note: WLS of Cerenkov photons not taken into account in this simulation.



Increased sensitivity to proton decay with WbLS

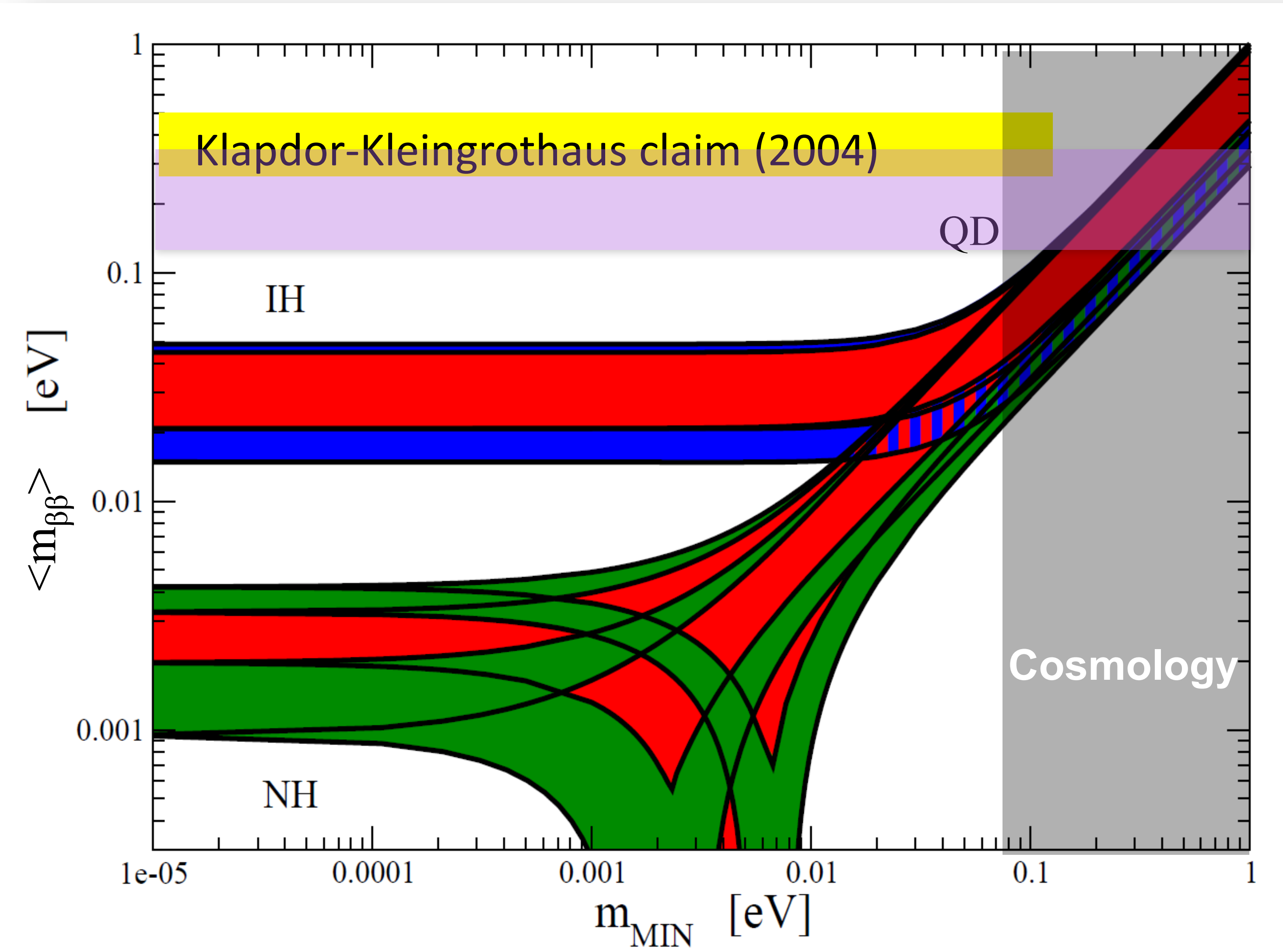


1. Main background is due to atmospheric muon neutrinos

2. Estimated signal efficiency of 88% based on selection on time, charge and particle ID with a background rejection of >99.975%

3. Expected 0.1 background per 10 years

Kinematically allowed Neutrino-less double-beta decay (0vββ) regions given knowledge of neutrinos



90%CL upper limit
$<m_{\beta\beta}> <$ 129-341 meV
$T_{1/2} > 1.9\times10^{25}$ yr
Exposure 85 kg.yr
P.Decowski, TAUP2013

Note: colored bands Indicate allowed variation of U_{ei} due to unknown Majorana phases and uncertainty in mixing angles

- $\langle m_{\beta\beta}\rangle^2 = |\sum_i U_{ei}^2 m_{\nu_i}|^2$
- m_{MIN} = lightest $m_{\nu i}$

R.D.McKeown, Report to Nuclear Science Advisory Committee,Neutrinoless Double Beta Decay, April 2014

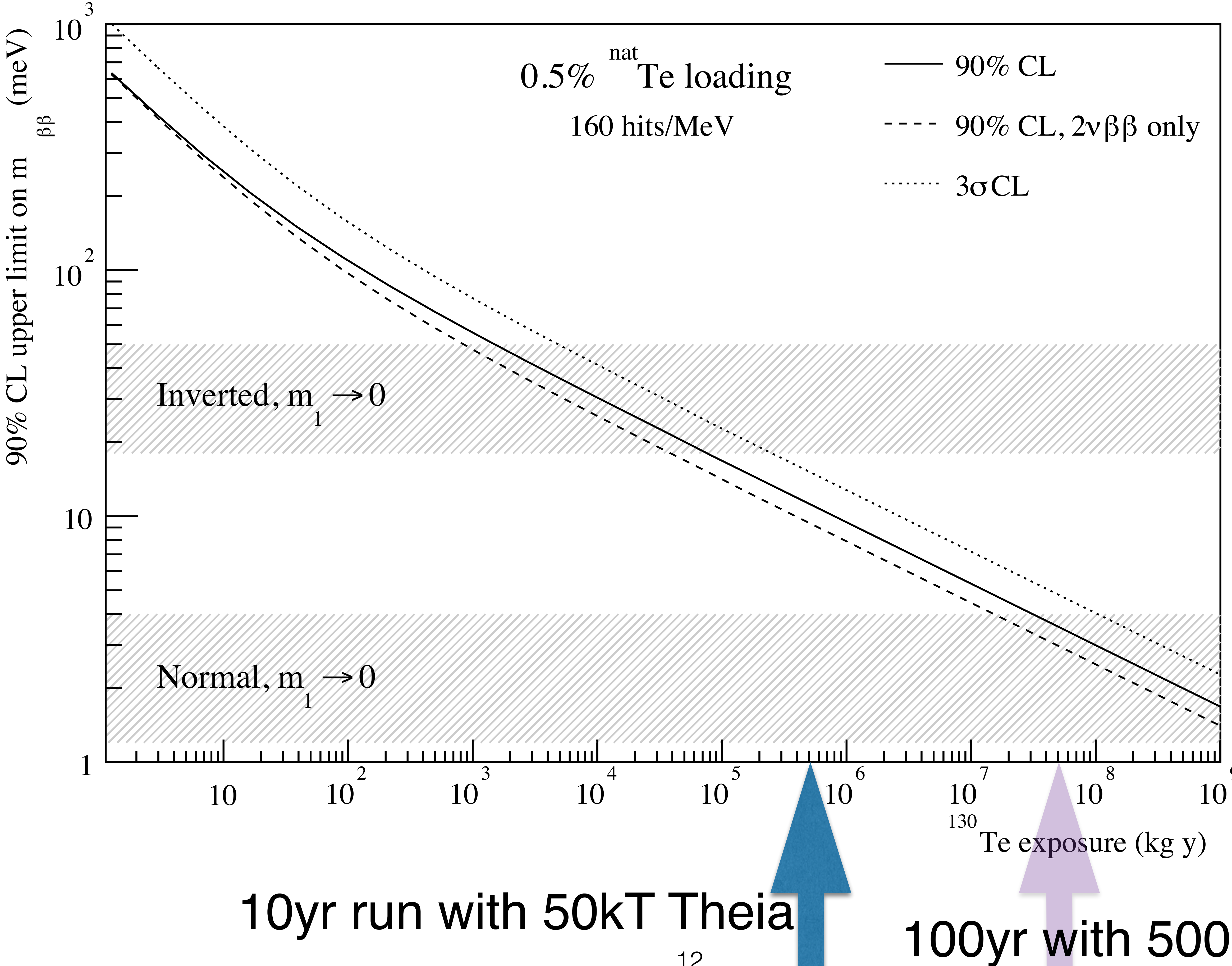
$0\nu\beta\beta$ with WbLS-based detector

1. SuperK-size (50kT) detector with **4%WbLS.** Need 5.5% energy resolution at $\beta\beta$ endpoint (~160 pe/MeV).

2. Nearly 100% photocathode coverage of high quantum efficiency photodetectors, eg. Hamamatsu R11780 or Large Area Picosecond PhotoDetector (LAPPD)

3. 0.5% loading of ^{nat}Te in WbLS would have ~50T ^{130}Te (34% abundance). Same $0\nu\beta\beta$ isotope as proposed for SNO+

4. Concept elaborated and discussed in http://arxiv.org/abs/1409.5864, "Advanced Scintillator Detector Concept (ASDC)…". Rich physics program including proton decay, solar neutrinos (^{7}Li loading of WbLS), geo-neutrinos, supernova neutrinos, diffuse supernova background neutrinos, long baseline neutrino physics (in conjunction with accelerator neutrino source), sterile neutrinos (in conjunction with neutrino source). ASDC also known as "Theia".



10yr run with 50kT Theia

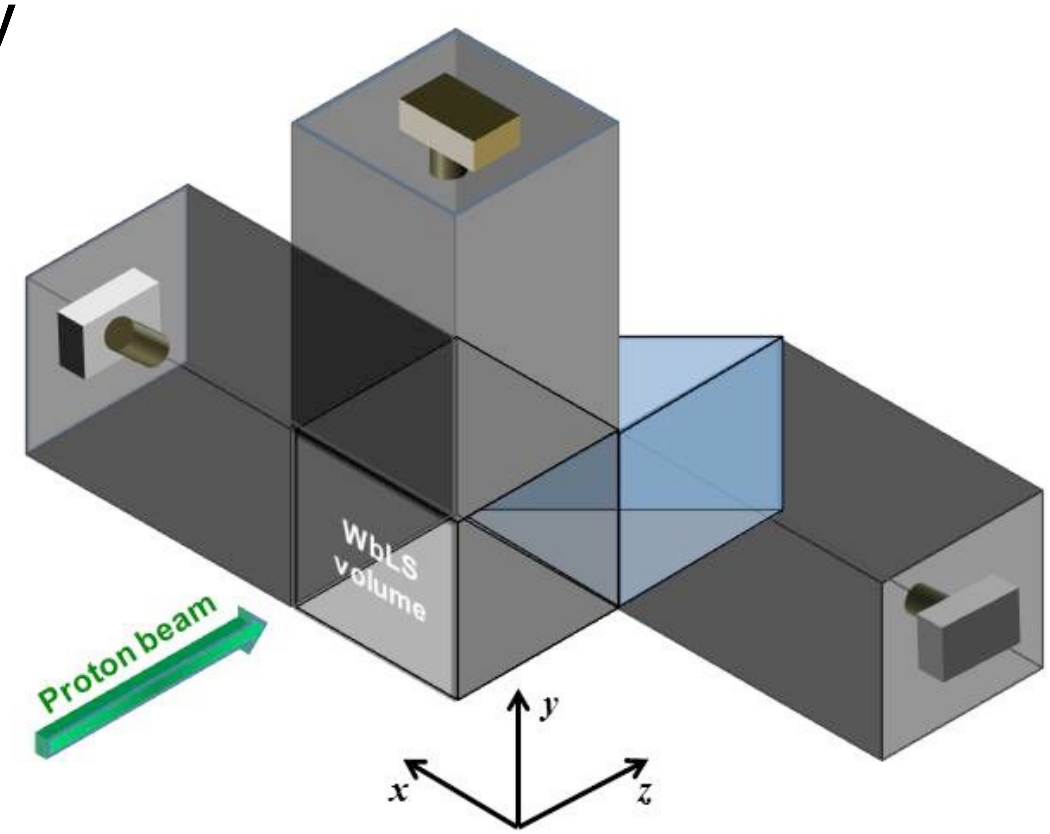
100yr with 500kT

Medical application of WbLS

1. Intensity-modulated pencil proton beam therapy (IMPT) in which a tumor can be targeted for radiation while sparing the surrounding healthy tissue.

2. Uses the Bragg peak of stopping protons to localize dose

3. WbLS-based “phantom” would serve as a real-time quality assurance device*



4. Requirements on WbLS:

    1. Able to withstand ~600Gy yearly facility dose

    2. Understanding of light yield and collection to ~1-2%.

    3. Millimeter scale position resolution

    4. ~5% concentration of LS in water (“5%WbLS”)

*Humans are “ugly bags of mostly water” - Star Trek Next Generation.

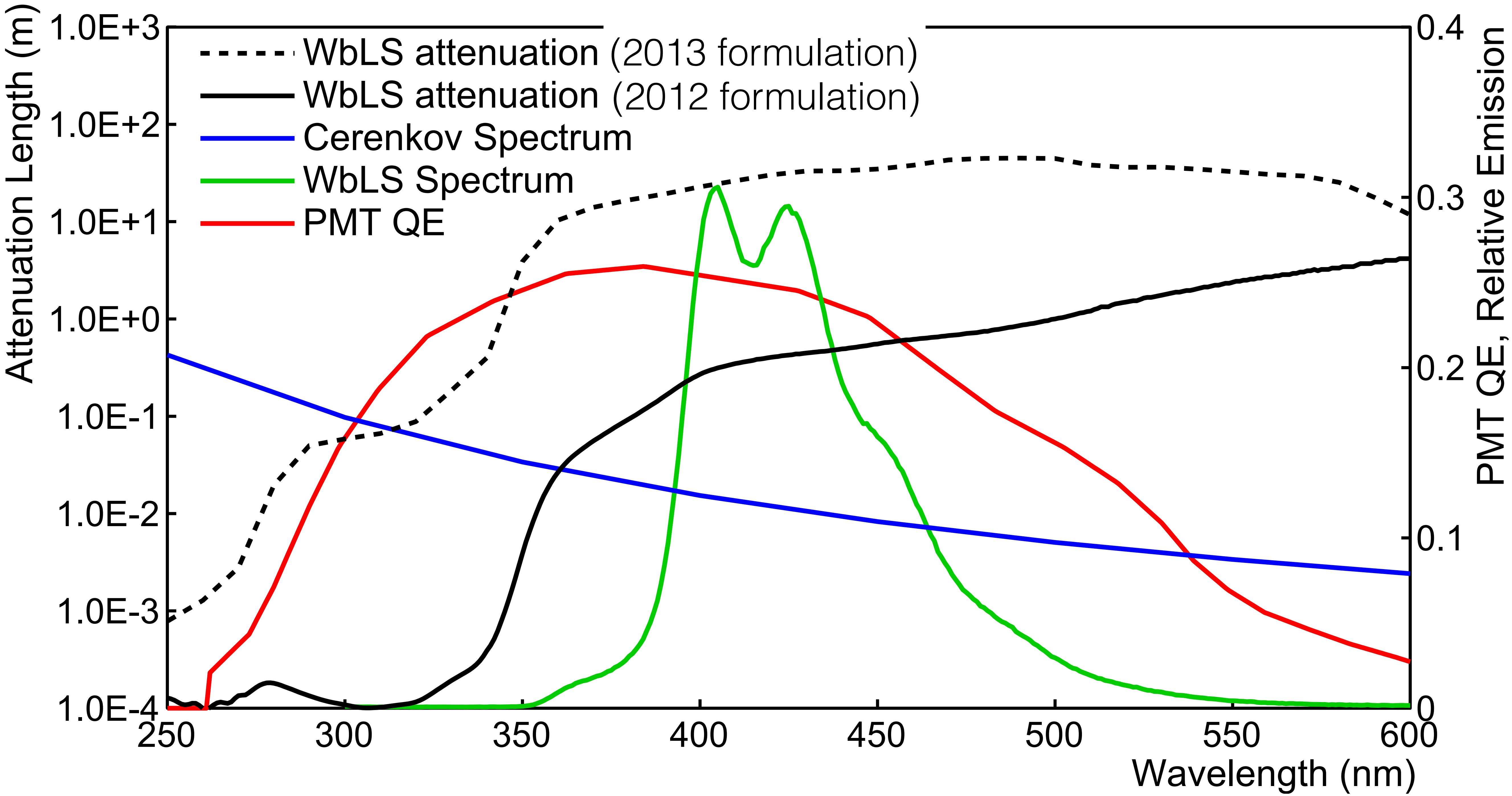
WbLS properties of interest

Light production & transport in water, LS and WbLS

1. Cerenkov (point source, directional, prompt)
    1. Light yield is calculable: N = (path length) X $N_0(\sin^2\Theta_C)$
    2. Spectrum LY(λ) $\propto 1/\lambda^2(1-\beta^2 n(\lambda)^2)$
2. Scintillation (point source, isotropic, extended in time)
    1. Light yield proportional to energy deposit, modulo quenching. Must be measured.
    2. Narrow spectrum
3. Absorption & re-emission (possibly diffuse source, isotropic, extended in time)
    1. Optical photons from Cerenkov or scintillation process can be absorbed and re-emitted by medium
    2. Has potential to shift Cerenkov photons from UV to visible for a typical photodetector (eg. bialkalai PMT)

Light yield for these processes is comparable for <10% concentration WbLS. Disentangling them and understanding the details of wavelength-dependence is the main focus of R&D.

Wavelength-dependence of attenuation, emission, PMT quantum efficiency



Light yield for these processes is comparable for <10% concentration WbLS. Disentangling them and understanding the details of wavelength-dependence is the main focus of R&D.

Characterizing WbLS

1. Light yield (photons/MeV)
2. Absorption & emission spectra
3. Quantum yield (#photons emitted/# photons absorbed)
4. Quenching
5. Pulse shape discrimination
6. Fluorescence & scintillation decay time
7. Attenuation length
8. Colloid size
9. Colloid electrokinetic or “zeta” potential
10. Stability
11. Compatibility
12. Radiation hardness
13. Metal-loading capability

Measurements

BNL R&D

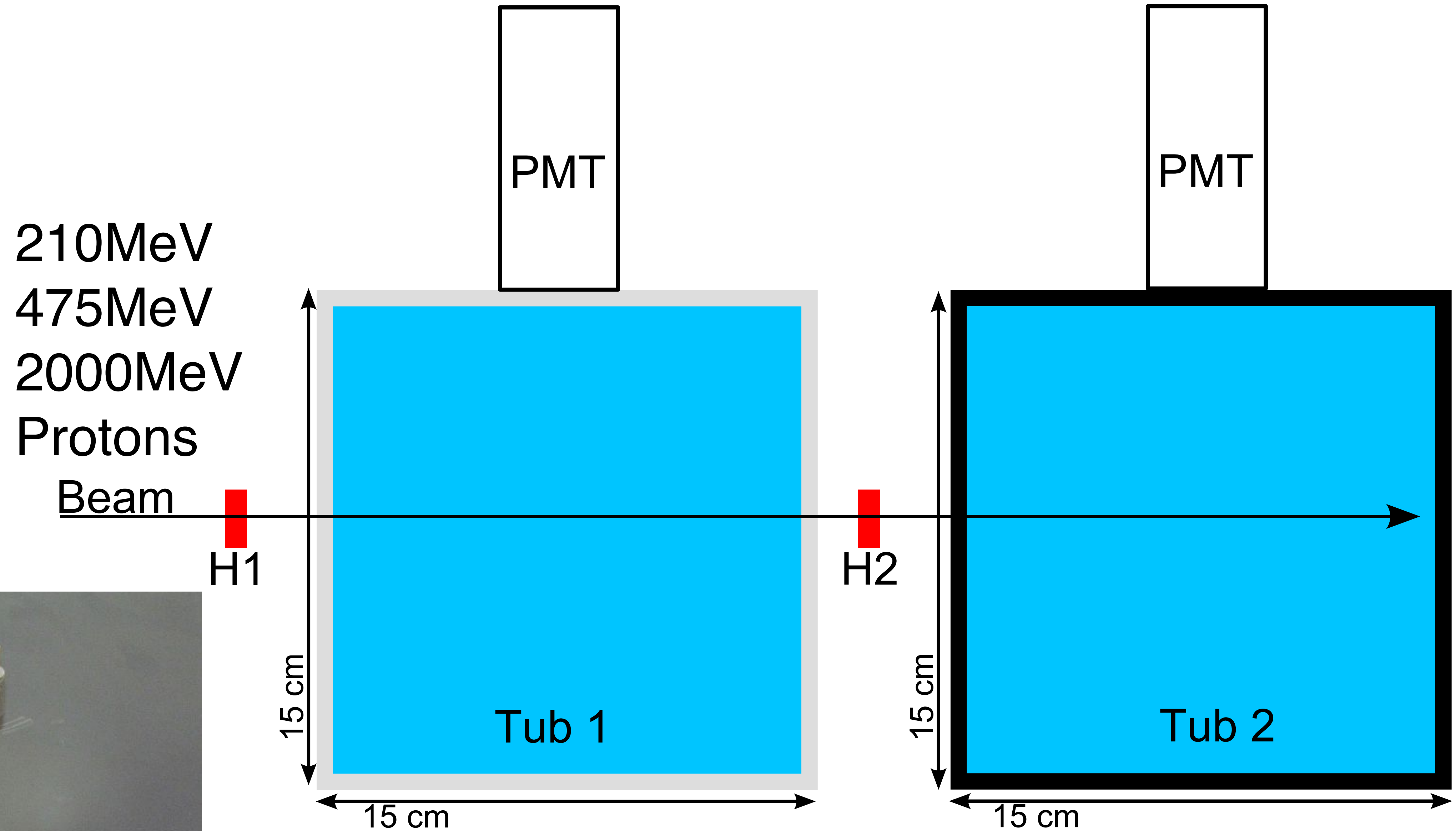
1. Samples investigated ("2012 WbLS" formulation)
   1. Pure water.
   2. 0.4% WbLS = "WbLS-1"

      0.4%PC (pseudocumene)+0.4g/L PPO+3mg/L MSB+ surfactant + water
   3. 1% WbLS = "WbLS-2"

      1.0%PC+1.36g/L PPO+7.48mg/L MSB + surfactant + water
   4. LS: LAB(Linear Alkyl Benzene) + 2g/L PPO + 15mg/L MSB.
2. Low energy proton beam data at NSRL (NASA Space Radiation Laboratory at BNL)
   1. *NSRL run 12C*: Measure light yield for 4 samples & investigate quenching with 2000 MeV (~minimum ionizing), 475 MeV (Cerenkov threshold in water), 210 MeV ($\beta p = \beta_K$ for $p \rightarrow K^+ \nu$)
   2. *NSRL run 13A*: Calibrate 1% WbLS light yield against Cerenkov light yield, disentangle competing light production processes with 2000 & 475 MeV beams
3. Fluorescence and UV-VIS spectrometry (absorption and (re-)emission)
4. Light yield from Compton-scattered electrons with a ^{137}Cs gamma source

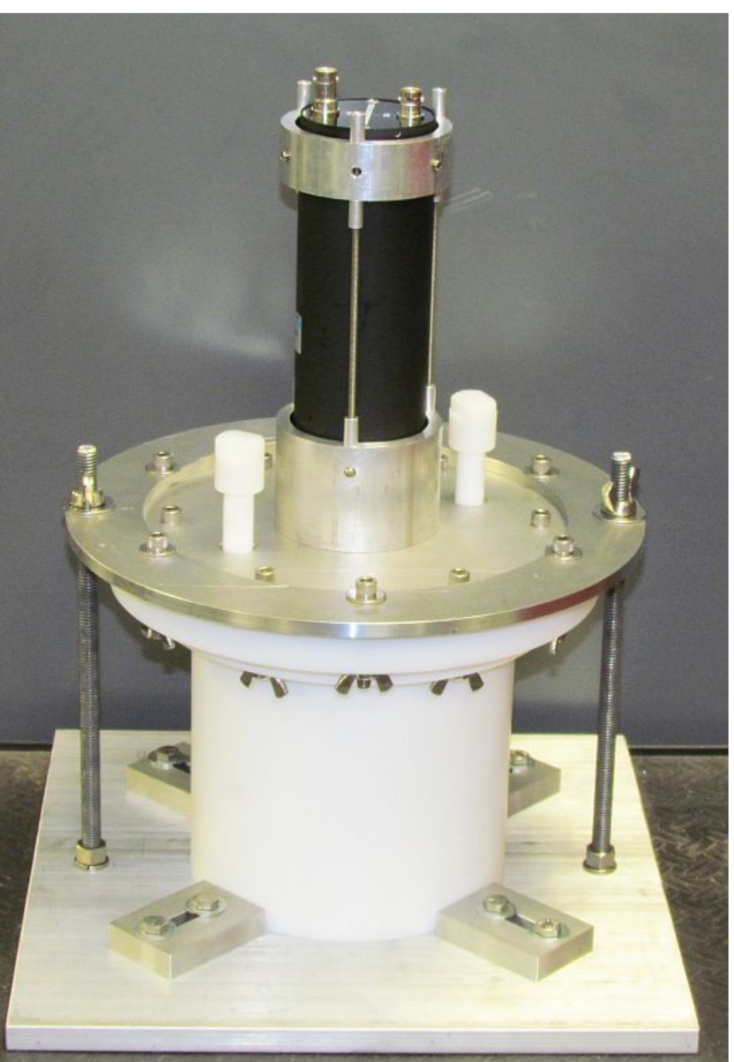
arXiv:1508.07029, submitted to JINST

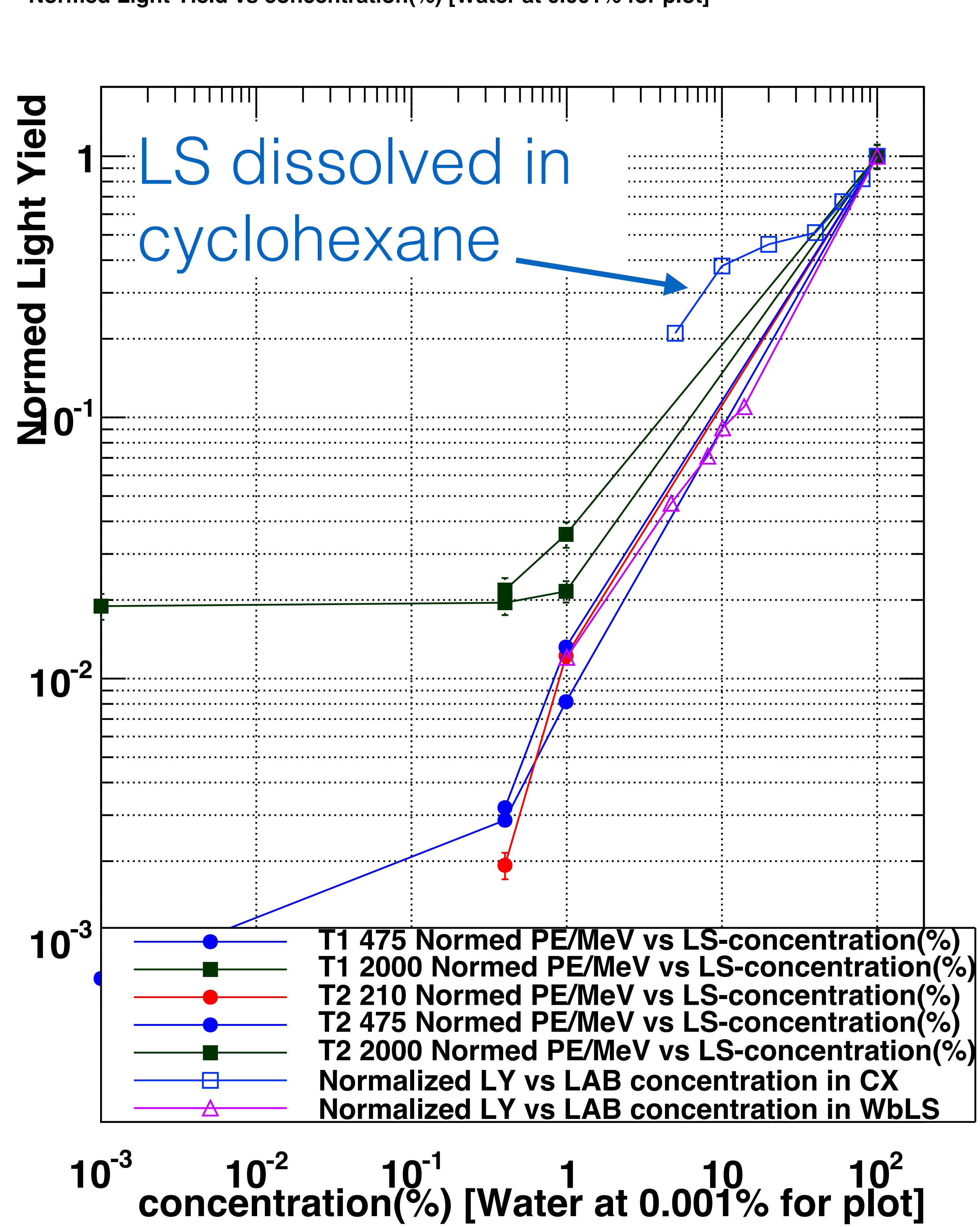
NSRL12C apparatus: Identical liquids in T1,T2



High-reflectivity white PTFE

Al coated with low reflectivity black PFA





Compare NSRL12C proton & Compton-edge data

Comparison of relative light yield of proton beam data with Compton-edge data for WbLS and LS dissolved in cyclohexane(CX)

1. Light yield roughly proportional to concentration in WbLS emulsion
2. In cyclohexane, light yield higher at low concentrations
3. Cerenkov effect apparent for 2000 MeV proton data

EXPERIMENTAL APPARATUS

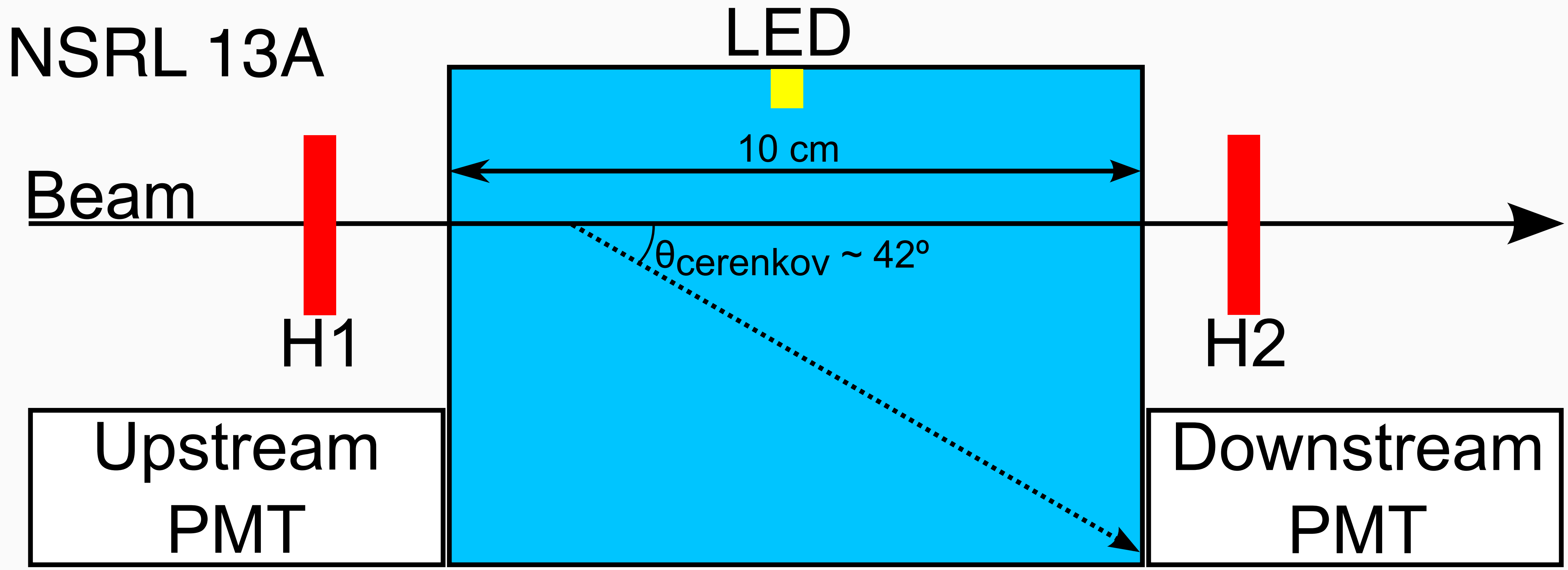


Figure: The beamline detector setup.

- Proton beam incident on 1% WbLS or water.
  - 1% WbLS: 1% Pseudocumene, 1.36 g/L PPO, 7.48 mg/L Bis-MSB, water, surfactant.
- Black ABS plastic vessel, UV-transparent acrylic windows to PMTs (Hamamatsu R7723).
- Plastic scintillator hodoscopes define 2 x 2 cm beam (H1 & H2).
- LED in target volume for in-situ single PE calibration.

L.Bignell, “Proton light yield measurements of a water-based liquid scintillator”, 2014 IEEE Nuclear Science Symposium and Medical Imaging Conference, Seattle

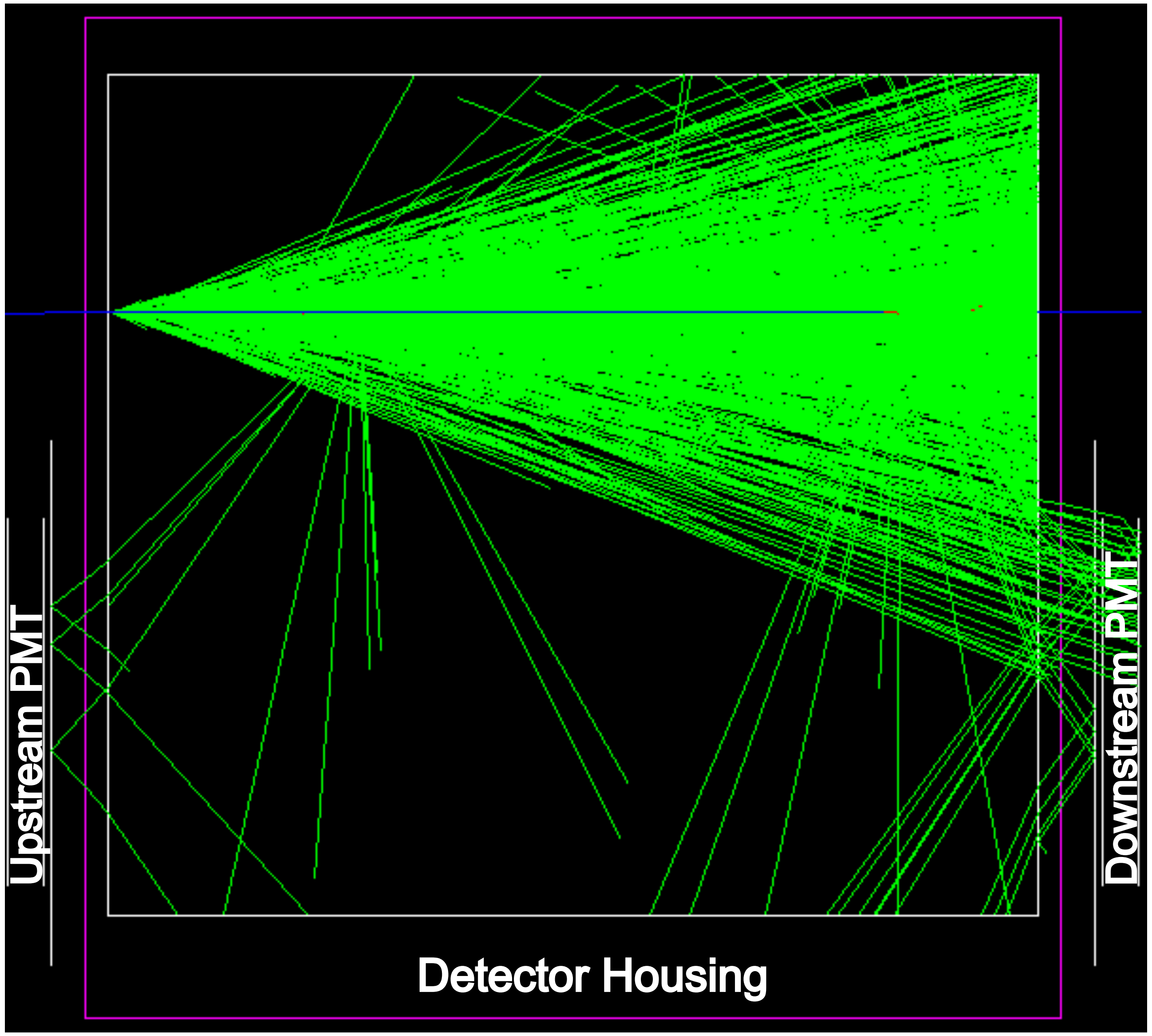
Geant4.10 simulation of the detector and hodoscopes, with customized wavelength-shifting (WLS) physics to incorporate:

- wavelength-dependent quantum yield[3]
- wavelength-dependent emission spectrum

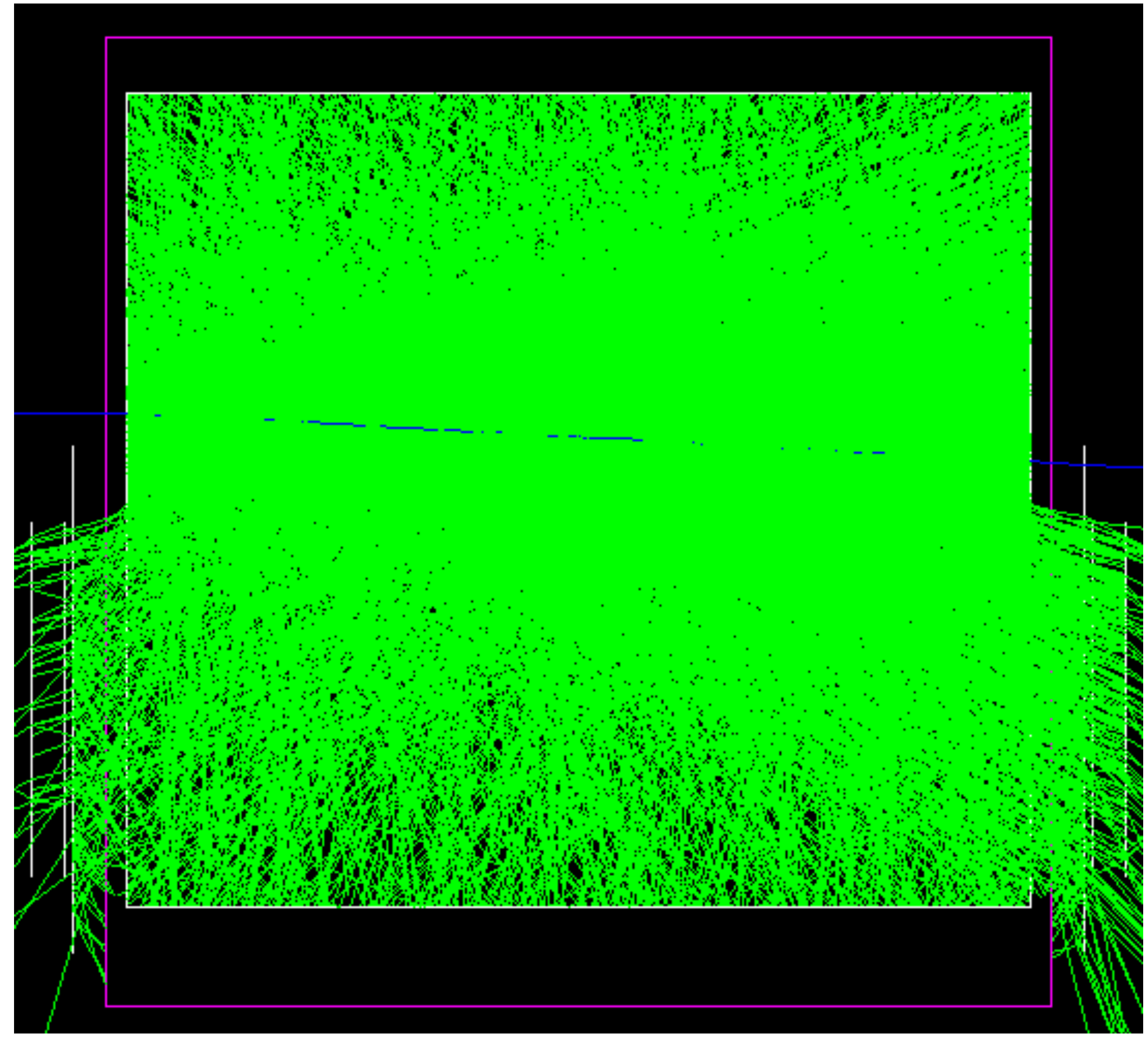
Wavelength-dependent PMT quantum efficiency implemented in readout.

Figure: A simulated 2 GeV proton (blue) event in water, with Cerenkov photons (green). The Cerenkov cone illuminates the downstream PMT. Cerenkov photons produced by secondary electrons are also visible.

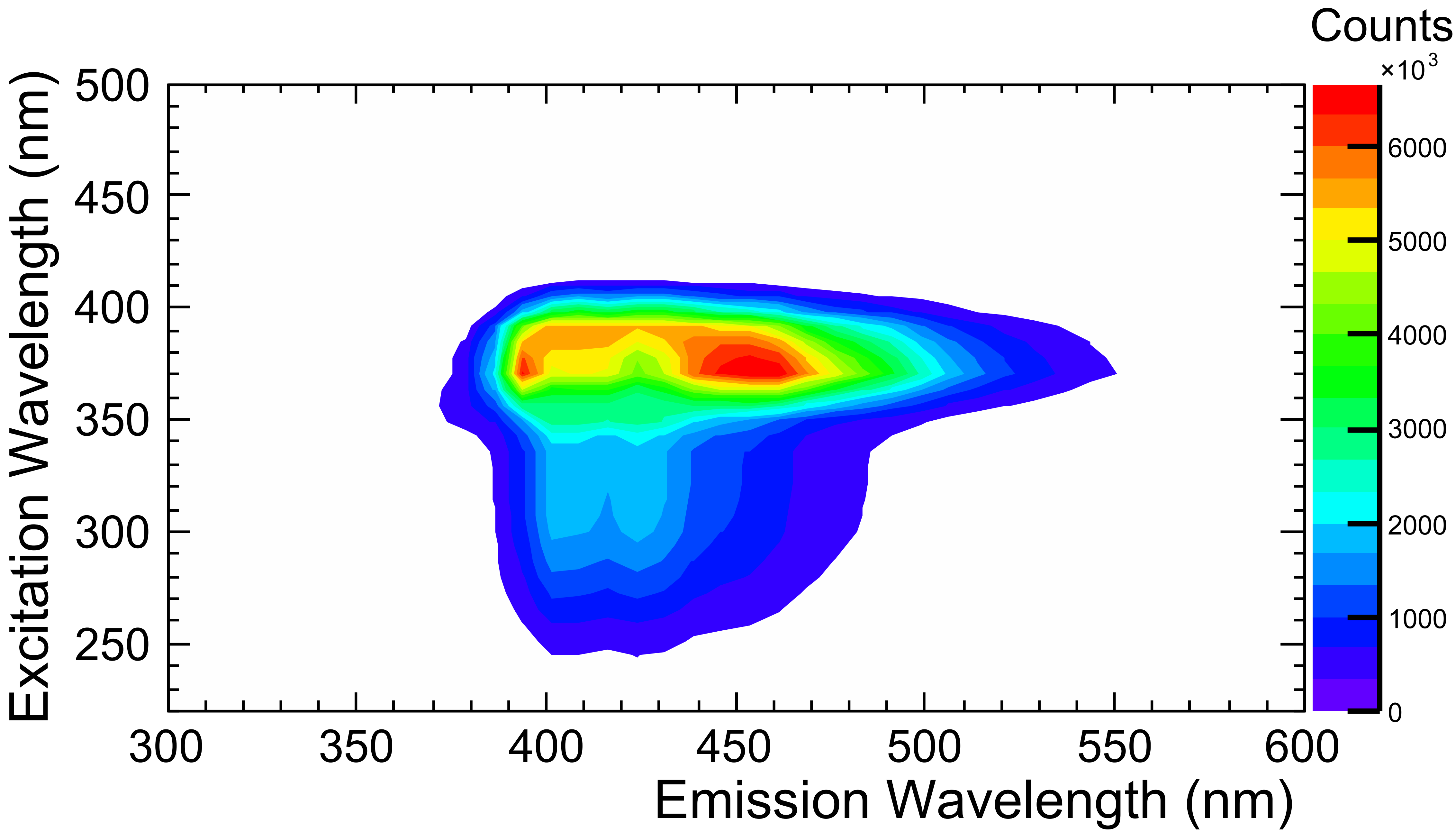
[3]The quantum yield of a fluorescent material is defined as the probability of emission, upon absorption of a photon.



Simulated 2000 MeV proton beam in water



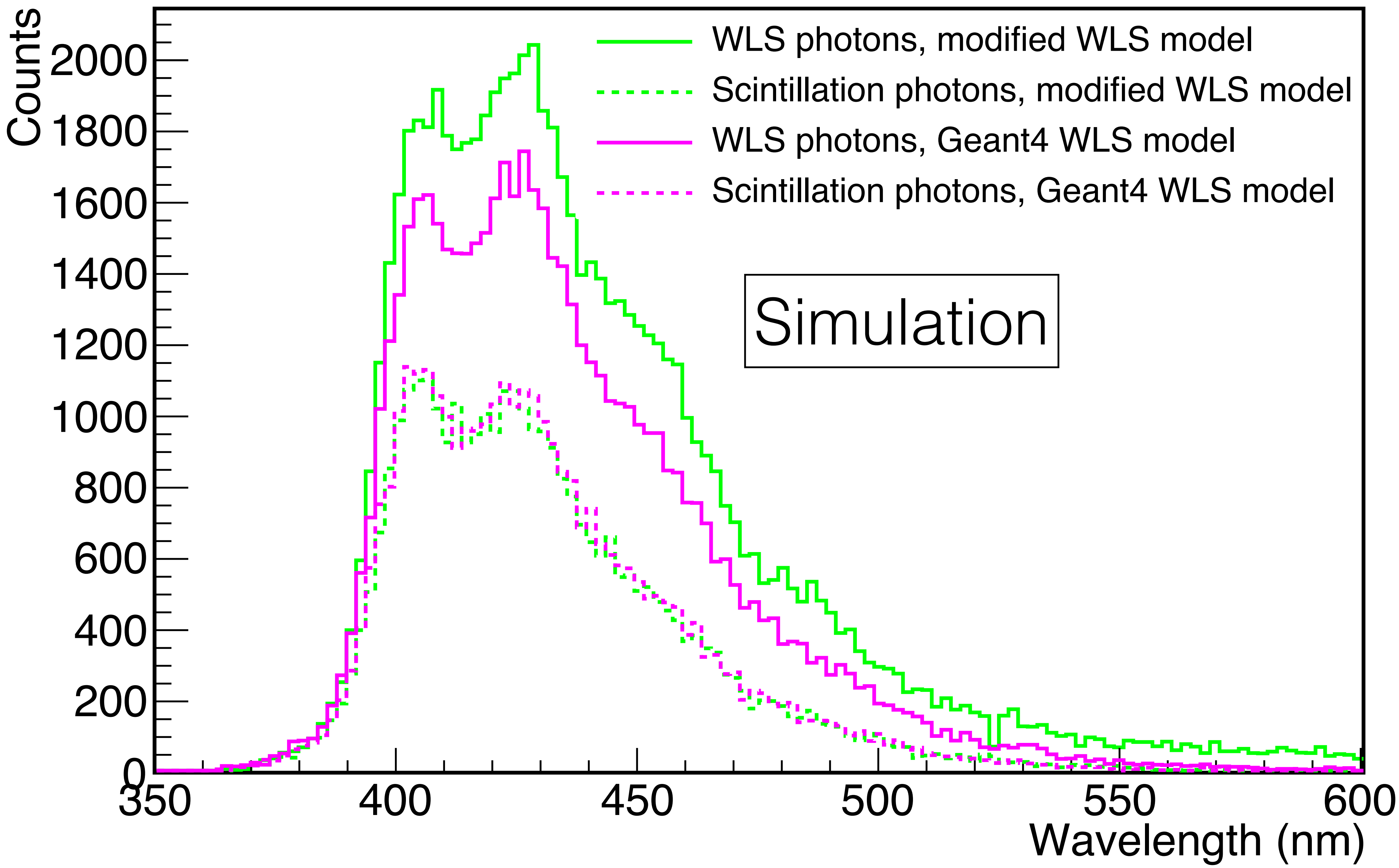
Simulated 2000 MeV proton beam in 1% WbLS



Excitation vs Emission for 1%WbLS

Measured with PTI fluorescence spectrometer and used in simulation

Predicted optical photon spectrum from WbLS for 2GeV

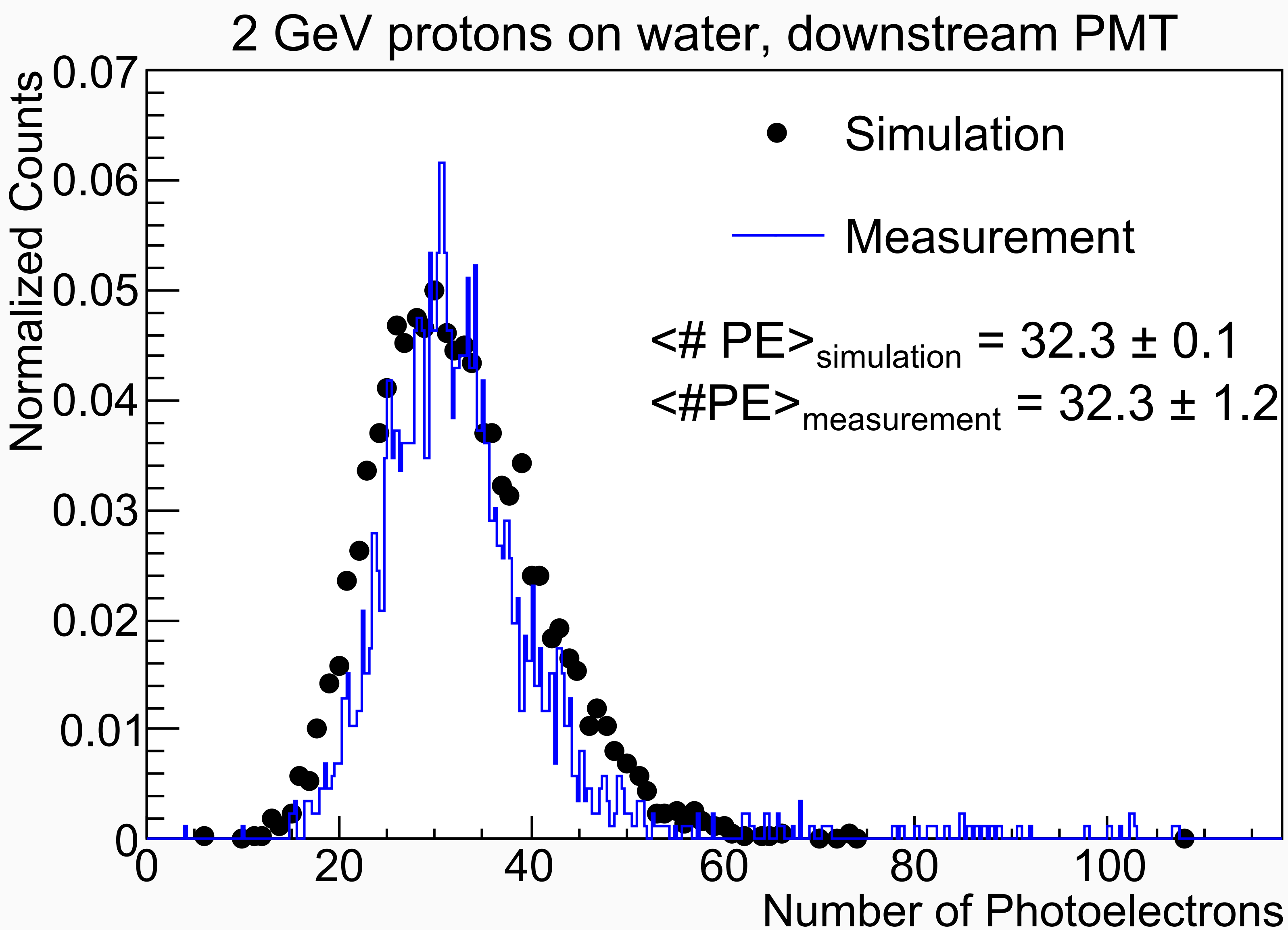


Modified WaveLength Shifting (WLS) model predicts 27% more WLS light and 20% more overall light from 1% WbLS in upstream PMT for 2 GeV protons

2 GeV protons on water – model calibration

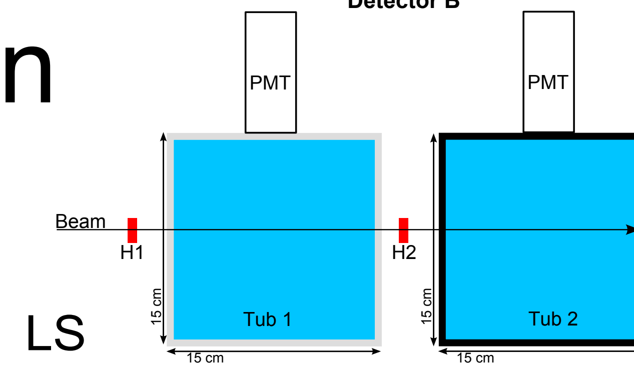
Simulated optical parameters were optimized to the water measurements.

2 GeV water measurements confirmed validity of simulated geometry and readout.

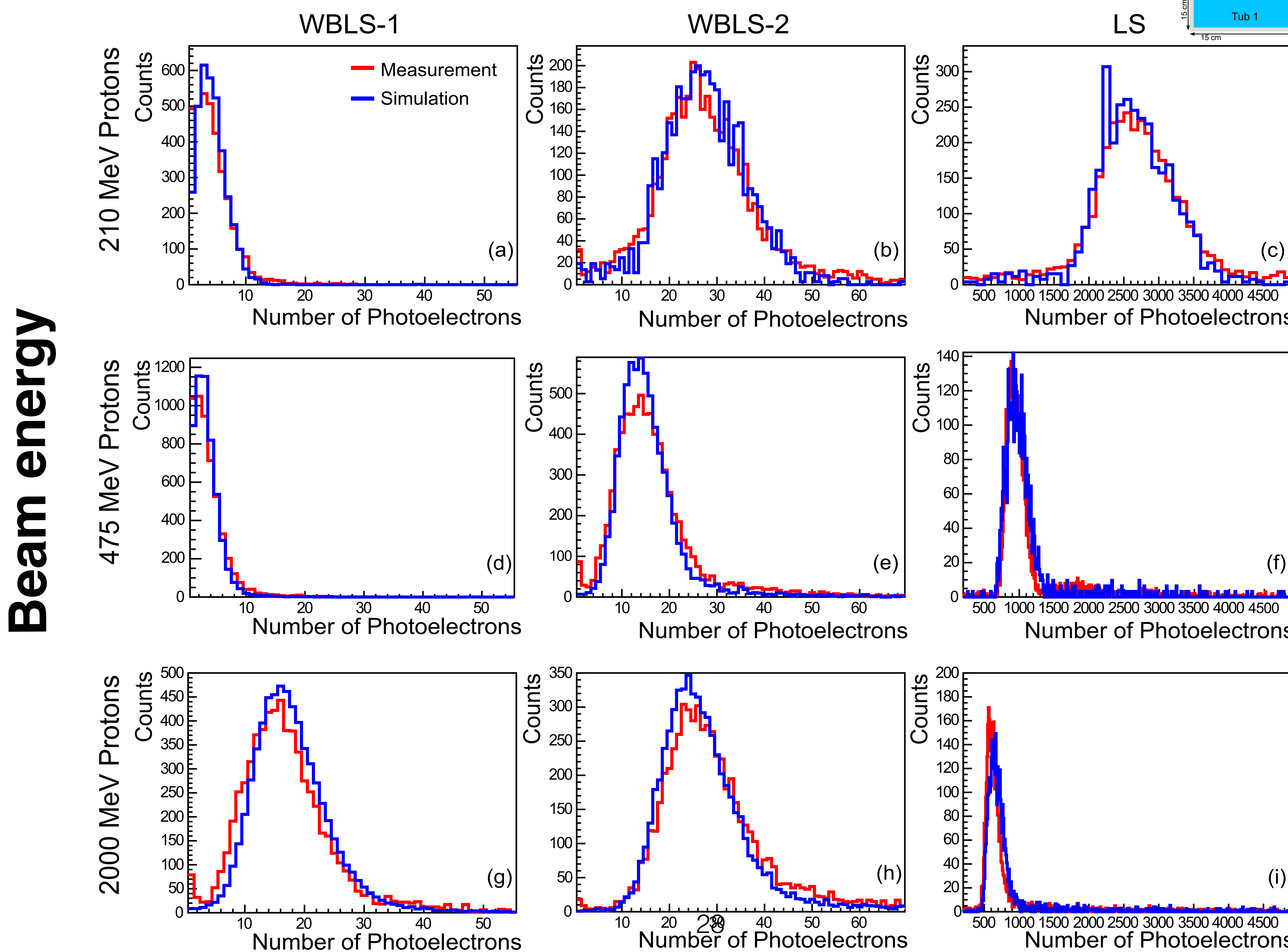


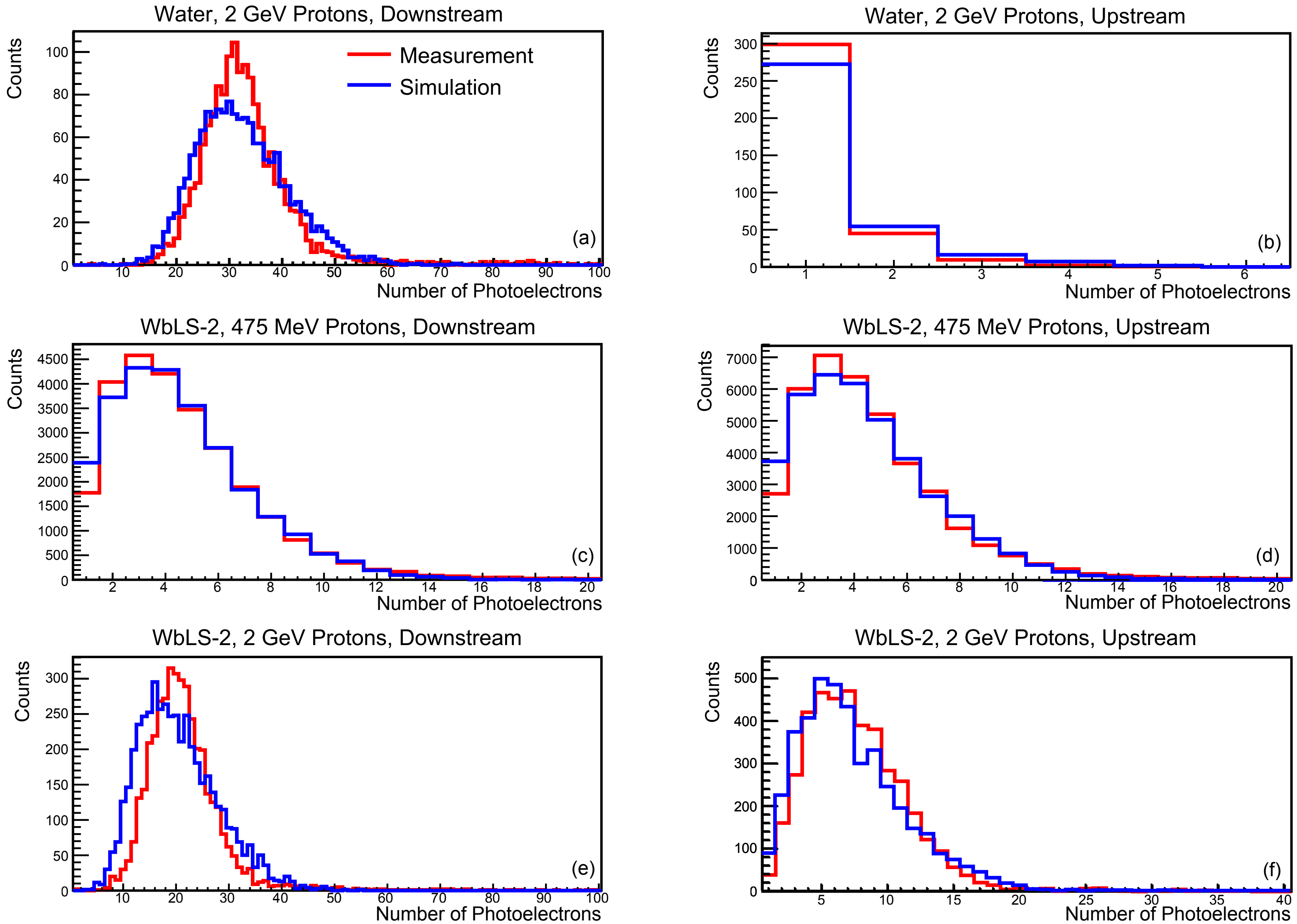
Slight difference in width of distributions not understood

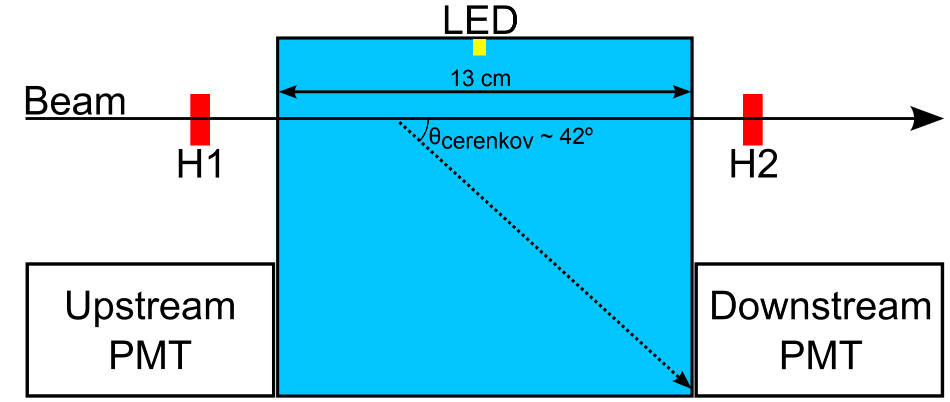
Comparison of NSRL12C data with simulation



Sample composition







Comparison of NSRL13A data with simulation

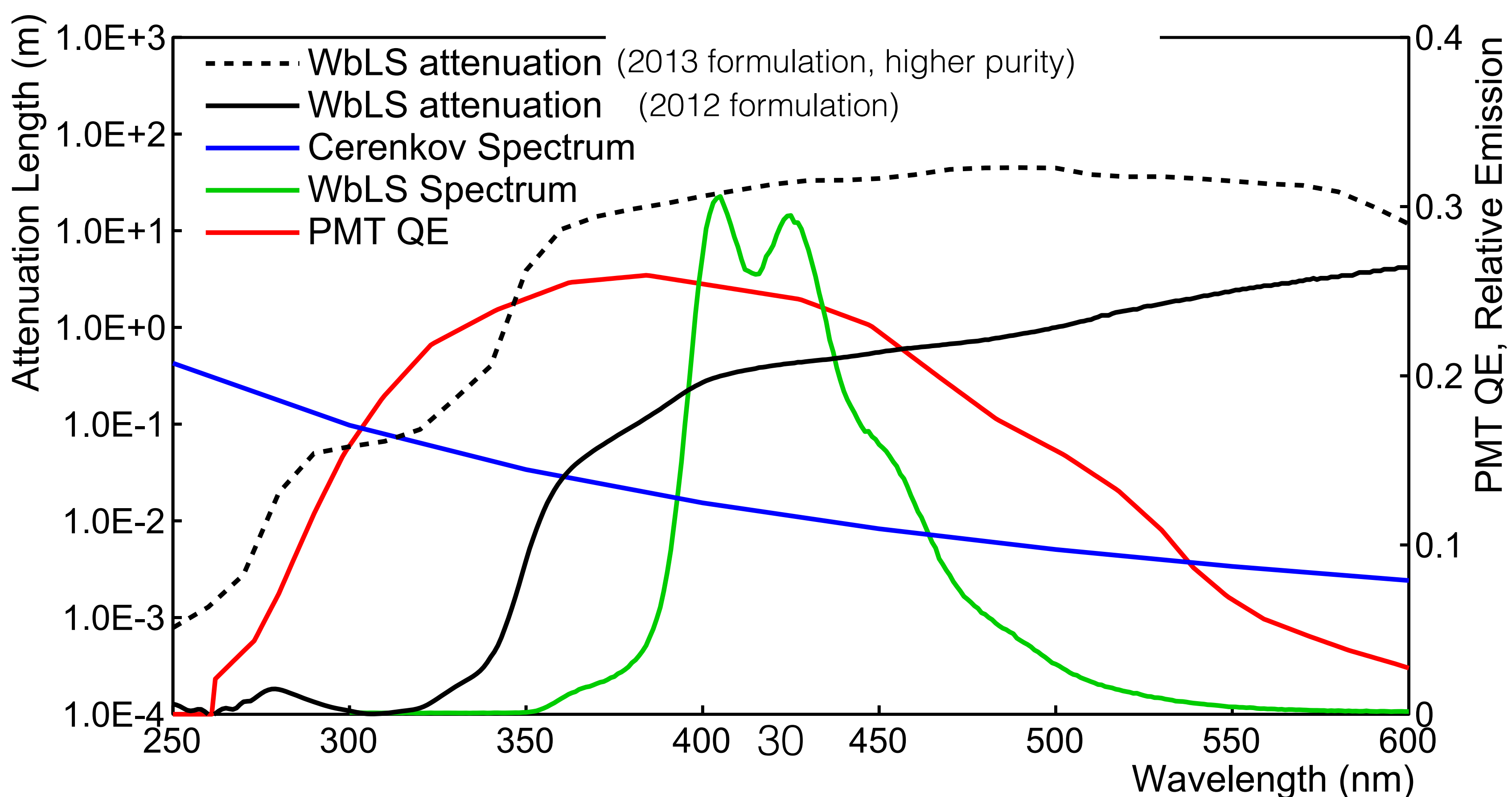
Mean number of photoelectrons

Sample	Incident Proton Energy	Photomultiplier	Measured	Simulated
Water	475 MeV	Downstream	1.3 ± 0.0	1.6 ± 0.2
Water	475 MeV	Upstream	1.2 ± 0.1	1.2 ± 0.1
Water	2000 MeV	Downstream	33.0 ± 0.2	32.4 ± 3.2
Water	2000 MeV	Upstream	1.2 ± 0.0	1.4 ± 0.1
WbLS-2	475 MeV	Downstream	4.7 ± 0.0	4.6 ± 0.5
WbLS-2	475 MeV	Upstream	4.6 ± 0.0	4.5 ± 0.5
WbLS-2	2000 MeV	Downstream	21.5 ± 0.3	20.4 ± 2.0
WbLS-2	2000 MeV	Upstream	7.7 ± 0.2	7.3 ± 0.7

Interplay of Cerenkov and scintillation light

1. Results on previous page indicate that 1.27±0.05 WLS-Cerenkov photons are detected for every detected scintillation photon. [Simulation: 1.28]

2. Absorption probability of detectable Cerenkov light in 1%WbLS at first order is ~ 58%. This would be unacceptable for a large detector. Improved WbLS has been developed.



Light yield and quenching parameters

Material	Light yield (photons/MeV)	kB (mm/MeV)
0.4%WbLS	19.9±2.3	0.70±0.14
1%WbLS	109±11	0.44±0.05
LS	9156±917	0.07±0.01

$$\frac{dL}{dx} = L_0 \frac{\frac{dE}{dx}}{1 + kB\frac{dE}{dx}}.$$

- LS light yield and kB consistent with other measurements in literature for LS and plastic scintillator (0.09<kB<0.19 mm/MeV)
- Light yield of 1% WbLS is ~1% of LS
- kB of WbLS significantly larger than LS.
  - Due to change in bulk LS properties when in emulsion?
  - Due to presence of surfactant and/or water?

WbLS is an emulsion

1. A surfactant is added to LS,water mixture to stabilize the emulsion. The surfactant has a hydrophobic “tail” and hydrophilic “head”.

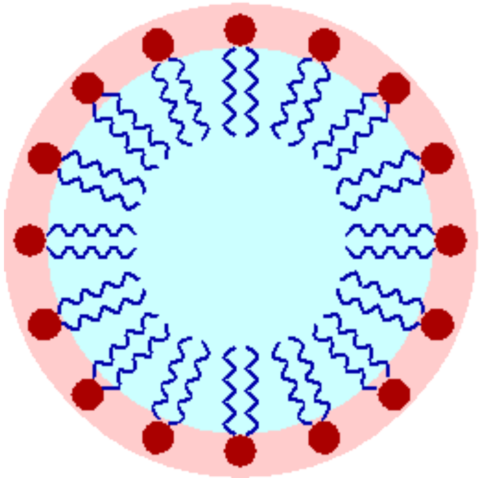
2. A micelle is an aggregate of surfactant molecules dispersed in a liquid colloid. For WbLS, the hydrophilic “head” is in contact with the water, the hydrophobic “tail” sequesters the LS.

3. Absorption length and preliminary diameter measurements suggest micelle diameters of O(10nm).

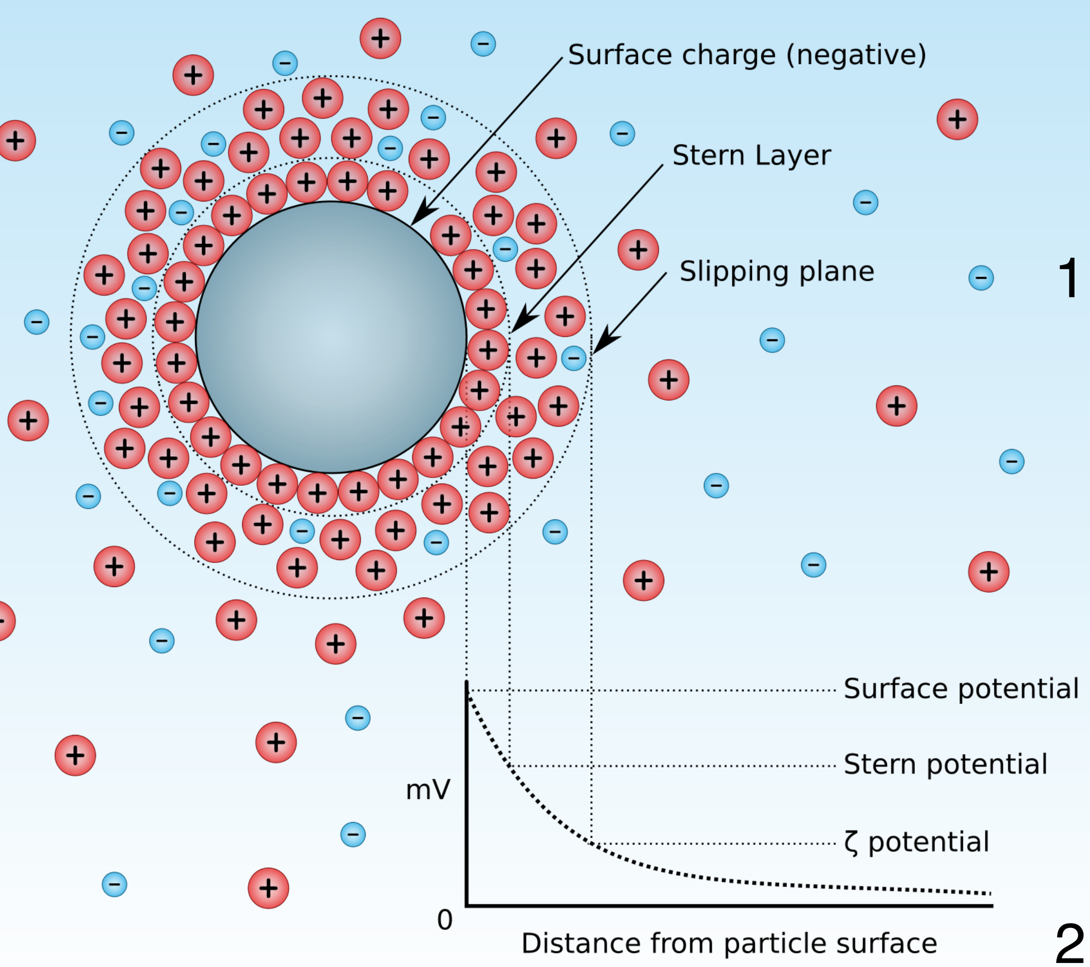
4. Sequestering the LS to a micelle

    1. Alters the effective diffusion length of the LS molecules which will change the probability of energy transfer and fluorescence decay time.

    2. Allow energy transfer to the surfactant and water affecting light yield/quenching



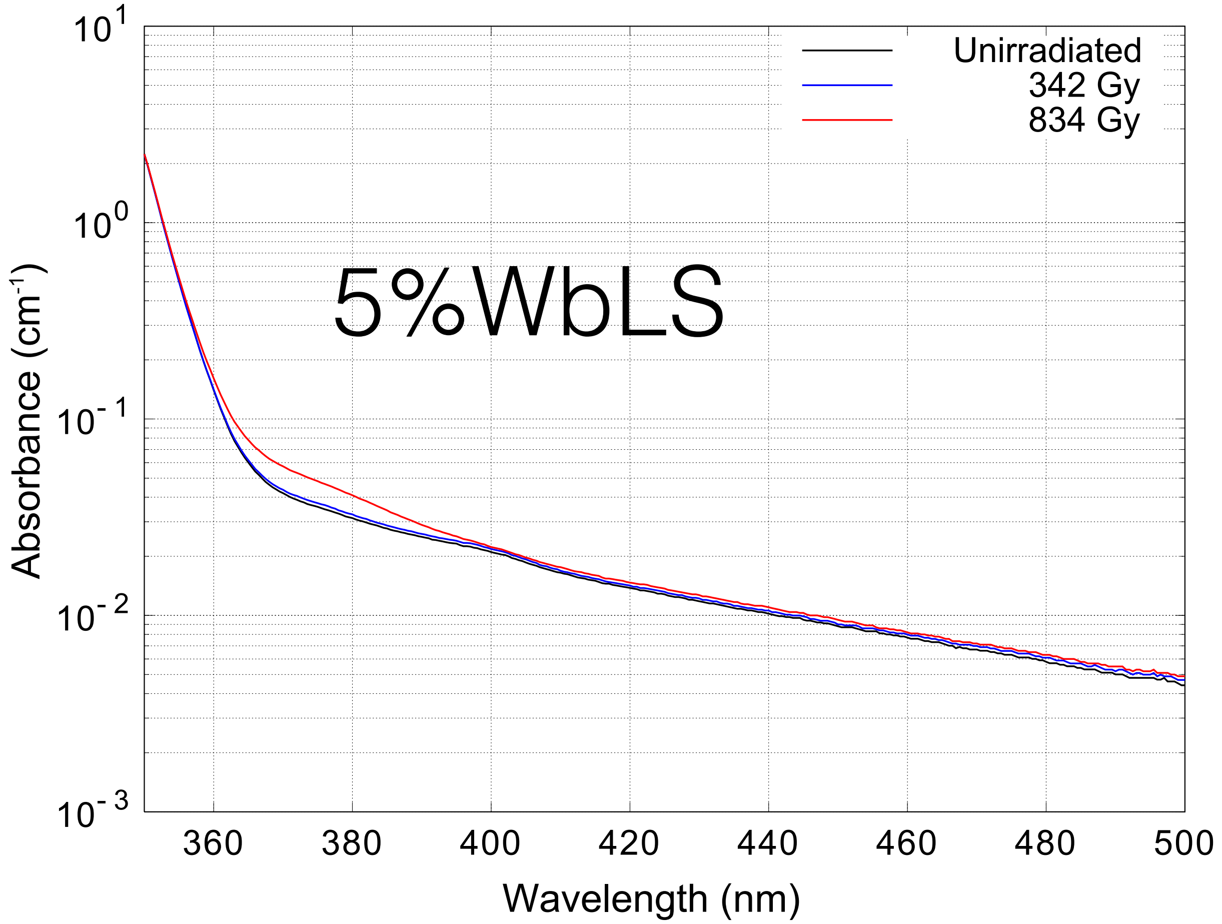
A micelle drawn in wikipedia

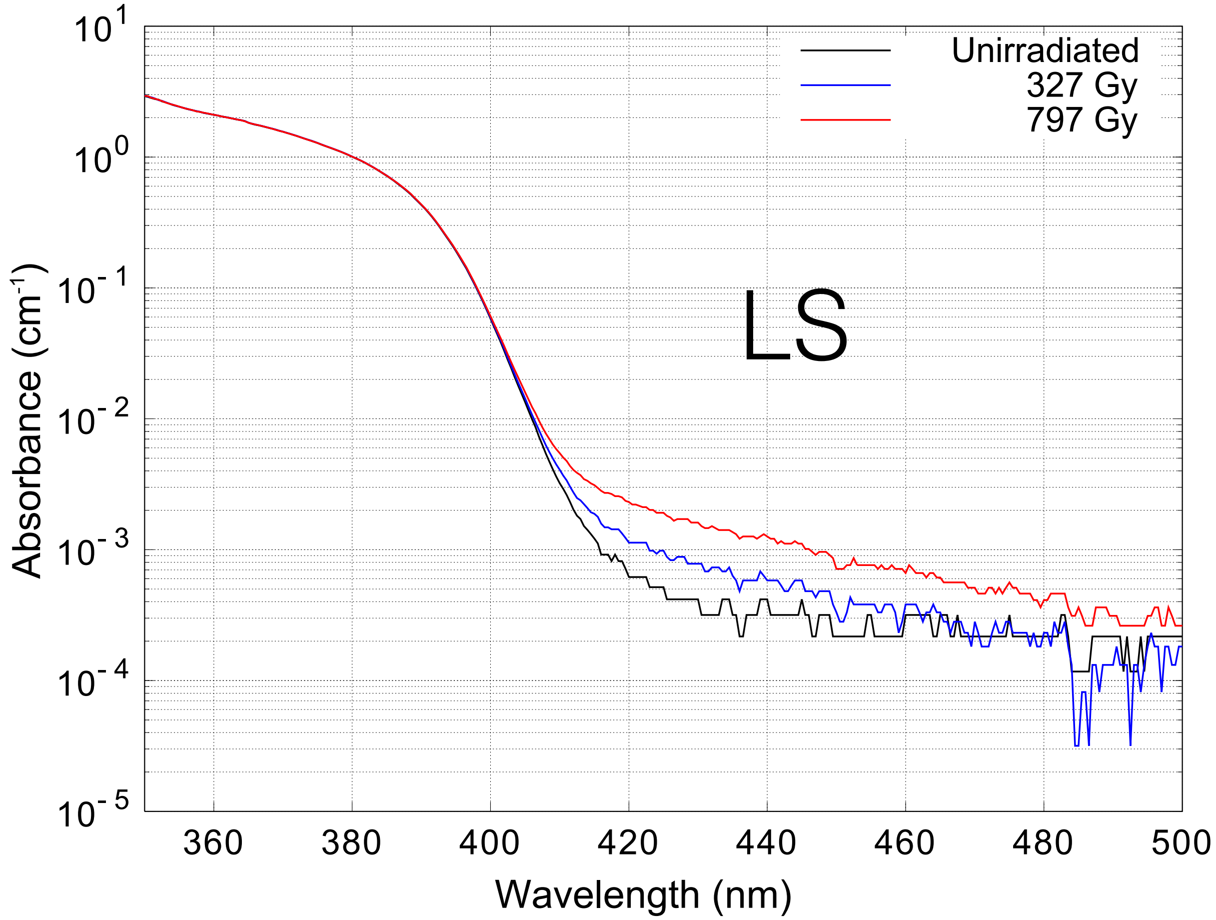


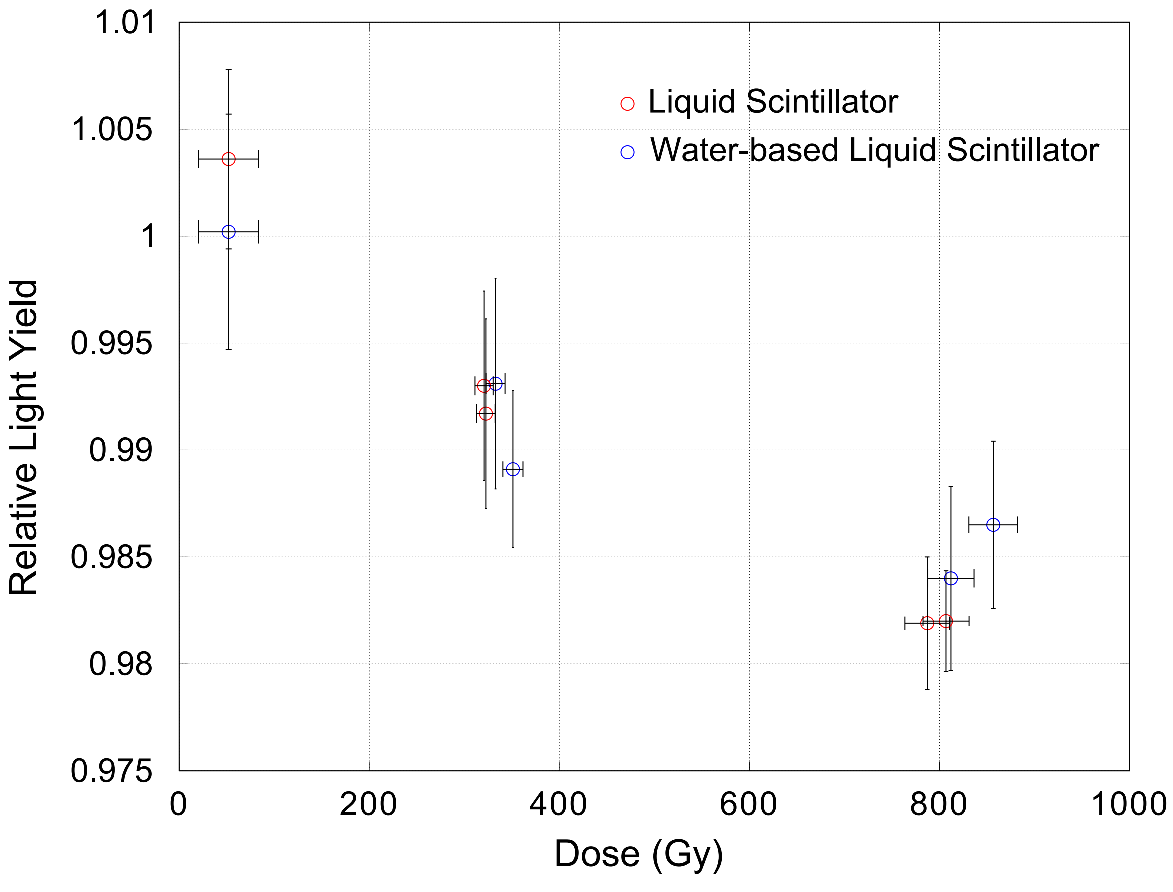
WbLS measurements in progress or beginning soon

1. Malvern Zetasizer Nano at BNL Center for Functional Nanomaterials (CFN) will be used to measure micelle size (dynamic light scattering) and ζ potential (electrophoretic light scattering)
    1. Micelle sizes affects scattering length, may affect light yield, quenching, decay time.
    2. Emulsion stability improves with increasing ζ potential.
2. Fluorescence decay time via Time-Correlated Single Photon Counting, Picoquant FT200TCSPC, at CFN
3. Direct attenuation length measurement with 2-m system (Nucl.Instrum.Meth. A637 (2011) 47-52) in BNL Chemistry.
4. Absolute quantum yield measurement using integrating sphere in BNL Chemistry
5. Quenching and pulse shape discrimination measurements, AmBe and ^{137}Cs sources, BNL Physics
6. Commissioning a 1000 liter prototype in BNL Physics

Radiation hardness







1. LY reduced 1.74±0.55% and 1.31±0.59% for LS,5%WbLS resp. after ~800Gy dose at NSRL

2. Implies ~0.1% LY reduction in one year of operation of a proton therapy QA device

arXiv:1508.07023, to be published in JINST
SBIR proposal submitted Sept.2015

Summary and prospects

1. Water-based liquid scintillator is a new detection medium invented at BNL with numerous possible applications
2. We have shown that the light yield is adjustable and begun developing a detailed simulation to account for all light production and absorption mechanisms
3. Further investigation underway to understand why WbLS properties differ from bulk LS
4. We are currently commissioning a 1000 liter acrylic vessel to study WbLS performance and characteristics in a modest scale detector
5. We also plan a suite of measurements of light yield, absorbance and emission for various WbLS concentrations to incorporate in simulation